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DISTRIBUTION OF TREE SPECIES

IN THE SUDAN

IN RELATION TO RAINFALL AND SOIL TEXTURE.

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INTRODUCTION

i. Purpose.

In this book an attempt is made to record the principal features of tree distribution in a dry tropic country of one million square miles, an area equal to that of western Europe, and to interpret that distribution in terms of soil and water factors.

Exhaustive lists of species have been omitted in the belief that it is more important to see the wood than to see the trees only.

A tendency has been noticeable in recent years to give greater attention to the physical factors of soil and water in the study of distribution.

Clements, after confessing that the bulk of the material which had come the way of investigators, including himself, was mesotropic material, says, in discussing his hydroseres and xeroseres :-

"With increasing study of desert and tropical succession it is probable that the direction of the water reaction will assume its basic importance".

Runkiaer (52 p. 7) writes :-

"The relationship, of plants to water, influences vegetation to such a degree that it is by far the most impotant factor in the plant climate".

Braun-Blanquet (5 p. 214) writes :-

"In the ecological characterization of plant communities the water (and air) capacity of the soil, will, in the future, demand more attention".

More recently in almost every study of African distribution in which the water relation has been emphasized, the admission in made or implied that :-

"The influence of the rainfall on local conditions is not proportional to its quantity" (49). (H.W. Moore.)

In the search for the key to the efficiency of rainfall, T.F. Chipp devised a "degrees of wetness" formula designed to express effective rainfall by incidence rather than by total. C.G. Trevor (43 p. 361) in describing a South African tour made during the Empire Forestry Conference in 1935, said :-

/"It is a

"It is a curious fact that usually the soil is poor where the rainfall is high, as in the south-east of the Cape Province, while it is comparatively fertile in the area of low rainfall".

The "degree of wetness" formula of Chipp and the Precipitation - Evaporation ratio of Transeau and Mayer have helped towards a fuller understanding of site values. In the agricultural sphere, conditions in the cases of some cultivated plants are still so obscure as to be known by such terms as "Gezira conditions" in the irrigated Sudan plains (68) or as "sudden death" among cloves in Zanzibar (61) or as "winter killing" without frost in America.

Such problems deserve reexamination, on purely physical lines, of the soils of the site, and it is believed that the site analysis and Rainfall-Texture theories presented here may suggest a new approach at least to some of these problems.

As Sir Frank Stockdale writes (61 p. 13) of the "sudden death" of cloves.

"The progressive spread may also be due, to a change in the moisture balance of the soil as result of its exposure to the sun".

Before judging what water can do for a species in a given site it is necessary to note what water has done, or is doing, to the soil of that site.

ii. Treatment.

Along its longitudinal axis the Sudan stretches for 1000 miles from the rainless desert in the north to the Congo border and closed forest in upwards of 1400 mms of rainfall.

The great length and small rainfall span of this axis make it a particularly suitable one on which to study the changes in species which, given uniform soil conditions, accompany even small changes in rainfall, changes which are more easily indentified here than where the rainfall axis is fore-shortened.

Part I gives those basic facts of geography, soils and climate, existing in the Sudan, which have strong influence on distribution.

Part II deals with the forest geography, summarized after twenty two years of service and travel throughout the area, dealing first with the major ecological formations and second with type species and their occurences as species.

/A system.

A system of distribution analysis by transects cut through rainfalls and through site types is offered as likely to be of value in the Sudan and elsewhere, and the relative moisture values of different site types is assessed.

Part III discusses the influence, on forest geography, of the paramount soil and water factors, offers, for the fuller interpretation of the facts of distribution, the concepts of the climatic climax soil, of the datum soil, and of the clay-water line or rainfall-soil texture ratio, and concludes with instances of the practical application of these.

Many, if not most, of the tree species for which an evaluation of moisture requirements is made are species common also in French Equatorial Africa, Northern Nigeria and adjacent territories.

iii. Acknowledgements.

For the soil analyses used in this paper the writer is indebted to B.W. Whitfeild, A.I.C., to H. Greene, D.Sc., formerly Government Chemists, to C.W. Snow, B.A., B.Sc., F.R.I.C. designate Chief of the Research Division Department of Agriculture and Forests, and to the Staff of their laboratories.

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Khartum
April 1946

PART I. CHAPTER I. The Geography and Climate of the Anglo-Egyptian Sudan.

(i) Rivers.

The territory covers close on 1,000,000 square miles between parallels 4° and 22° of North latitude, and between longitudes 22° E. and 39° E. It includes a large part of the Nile Basin without including the source of either main branch, Blue Nile or White Nile, and without contributing, to either river, rainfall runoff in proportion to its extent of the total catchment of the River Nile. The Congo has a discharge of twelve times the amount per square kilometre of that of the Nile (42 p. 57).

The Niles depend principally on run-off from the Abyssinian and East African high country. This they receive before they enter the Sudan plains, except that two rivers Sobat and Atbara join the Nile in the Sudan having risen in Abyssinia.

The only material contribution to their regime arising from rainfall in the Sudan is made by a series of small rivers, the Arab, Lol, Nummatinna, Busseries, Sueh, Tonj, Gel and Naam all of which spill from the south-west into the great southern swamp zone and have little hydrological significance in the later regime of the main Nile. On the average only half the discharge of the main river passing Mongalla reaches the tail of the swamps, and practically all the water passing the tail of the swamps comes into the Sudan from the great lakes (42 pp. 18-19). The small tributaries mentioned rise along the Nile-Congo divide and drain the red laterite soils to the great swamp. The swamp tends to flatten out seasonal fluctuations in the flow of its effluvient the White Nile, which shows less seasonal rise and fall than the Blue Nile.

These differences have a markedly diverse effect on riparian vegetation, and indeed on riparian soils, producing two different types of high rise and low rise conditions.

But even the low rise conditions on the White Nile exercise a vital effect many miles from its banks since the rise, due to the denuded and burned state of the highlands of its catchment, is large enough each season to impede drainage flow in its lower basins, and to impound rain waters over a wide flood plain, for periods long enough to govern the nature of the soils themselves as well as of the vegetation.

(ii) Contour.

The central and eastern Sudan is essentially a country of ancient plains. In parts of Darfur the plains

/condition is

condition is extending with geological rapidity. The most important hills are limited massifs in the rainless parts of the Nubian sandstone desert (which persist for lack of rain), the Nuba Mountains group in Kordofan, with satellite outliers, a significant one of which is Jebel Daier, the Imatong-Acholi range in eastern Equatoria Province, Jebel Marra in Darfur. Towards the Nile Congo divide the country is undulating, and the divide is not, in altitude, a marked feature. The Ingessana hills are an insignificant group in the east, outliers of the Abyssinian hills. All save the desert hills are shown in Plate I.

The ironstone region of the south west is a country of gently undulating and low plateaux far on the way towards development into a plain, but still well drained because of their elevation and soil character. In the extreme east the toes only of the Abyssinian foot-hills penetrate the Sudan, the most significant representatives being the plateaux of eastern Equatoria province. Parallel with the Red Sea a chain of hills runs along the Sudan coast from the Eritrean border to the frontier with Egypt. Other hills and hill groups must be regarded as mere inselbergs persisting in the surrounding plain because of the indurated or otherwise resistant minerals composing their rocks, and exerting no influence on vegetation other than on that which they carry upon themselves or upon the narrow annulus, plinth or halo, of recent gritty detritus which separates the rock bases of each from the clay levels of the surrounding plains.

(iii) Rainfall.

There are two rainfall regimes, one of summer rains between May and October prevailing over nine-tenths of the Sudan, and the other of limited winter rains affecting only the Red Sea hills and the coastal plain at their eastern base.

Wadi Halfa on the northern frontier seldom records measurable rain. The Yei, Meridi and Yambio districts of Equatoria Province record an average of 1400 mms.

Between these two extremes the rainfall in general increases southwards. The most marked exception is a decrease in rainfall from the Central Sudan towards the south east corner.

Towards Lake Rudolf arid conditions are repeated on a latitude of 6 N. These areas are contiguous with the arid zones of Uganda, north east Kenya and of southern Abyssinia. A dry corridor is traceable through to the Somaliland coast and this is commonly accepted as due to the break between the massifs of Abyssinia and of British East Africa, though the meteorologists have still to speak with authoritative voice on this subject.

/The isohyets

The isohyets so far as are known, are shown in the appended chart. (Plate II). The Egyptian service has accumulated data for many years. These have been brought up todate by the Sudan Meteorological Service; practical agriculturists, forest officers and others have so far had little reason for querying their long-term accuracy.

On the 1400 mms. isohyet the rains may be expected to begin as early as late March and early April and late rains are common until early November. In the 200 mms. isohyet as at Khartoum, little rain falls outside July, August and September. That is to say, the duration of the period in which rain falls decreases northwards. In the south east corner there is a tendency for the rains to fall in two definite periods astride a dry spell. This regime is traceable as far west as Juba and in certain seasons as far as Yei.

Very occasionally light local showers occur in the dry season. In long grass country these are often induced by heavy grass fires. Condensation to form cloud can be seen taking place over a smoke column and rain showers are experienced limited to two or three hundred acres from clouds whose formation can be watched over grass smoke in a clear sky. To the vegetation such precipitations are insignificant, and they are unaccompanied by any general rise in humidity.

(iv) Temperature.

In the rainless north the peak of summer heat is reached in June, July and August. Proceeding southwards rainfall advances the temperature peak date while tending to make it less extreme. Thus in 200 mms. at Khartoum the peak occurs in May, in 800 mms at Malakal in early April, and in western Equatoria province in March or even late February. The onset of the rains is accompanied by a fall in temperature and a period of high humidity follows them, with temperatures rising again until the wind blows from the north in early November.

(v) Winds.

Temperatures are influenced closely by prevailing wind direction. The prevailing surface wind from late October until May, i.e. in the dry season, is from the northern deserts. This wind brings the extremes of winter cold. In the north western parts of Darfur and the northern desert, ice has been reported on many occasions, but save at 7500' on Jebel Marra in the crater bed, no frost and, save for hailstones, no climatic ice, has been seen in the Sudan by the writer. This wind direction in the dry season has been a prime factor in the surface carriage southwards of sand, silt, and seeds which are fixed at their southern termini by

/the rains,

the rains, and by the consequent vegetation, before a south wind can return them northwards.

The extremes of summer heat occur at the end of the season of north wind. In May at Khartoum, earlier in the south and later in the north, the wind turns and blows from the south heralding eventual rain. The approaching change is marked in the 200 mms isohyet by occasional violent dust storms generally from the south from April until early July.

Walls of dense brown dust up to 8,000 feet high and extending across fifty to a hundred miles of frontage, roll northwards over the clay plains which are their collecting grounds. These storms HAVE more significance as indicating the conditions of soil cover which prevail over their collecting grounds than as factors influencing vegetation. They resemble "dust bowl" conditions described in the United States of America, but do not erode the surface in depth. They are also significant as being the only aeolian return, on a substantial scale, of soil materials northward which can be seen taking place today. Temperatures rise in October and only fall when the wind blows again from the north in the first days of November.

It is not proposed to enter the field as the protagonist of aeolian or of alluvial origin for the clays of the great plains. The origin of the materials out of which these soils in the Sudan have been formed is of less importance than the present conditions of the materials, and their present conditions and probably their very existence are the result of geologically recent climate. The increase in clay content southwards has by some been assumed as proof of an aeolian origin which so acted that the finest particles were carried furthest south. But since in any single Sudan zone clay content within the zone is seen to vary with the soil-water relation, clay increasing with surface water, there is no means of discounting a similar soil-water reason for the

/increase of

increase of clay southwards across the zones into increasing rainfall. "The agent" (in soil distribution) "has relatively little effect upon the succession". (17 p. 35)

(vi) Humidity.

The following figures are given for the normal values of percentage relative humidity at :- Khartoum, representing the moist side of the Acacia Desert-Scrub belt; Malakal representing the moist side of the Acacia-Tall-Grass Country, and Wau, representing the drier edge of Mixed Deciduous Forest, or, in the older term, broadleaved savannah forest :-

Station	Period	January	April	July	October	Year
Khartoum	1900-25	29	15	47	31	31
Malakal	1915-25	30	46	84	80	58
Wau	1902-25	42	58	78	77	63

The above figures are compiled by the Egyptian Ministry of Public Works from records made in the Sudan on their behalf.

(vii) Soils.

The following brief outline of the classes and geographical distribution of the main soil types is included in this introductory chapter.

The accompanying map (Plate I) shows, as far as is possible on a scale of nearly 200 miles to the inch, distribution of the following main types :-

(a) Hill and valley soils.
(b) Red ironstone soils.
(c) The clay plains.
(d) The great swamps.
(e) The sands of Kordofan and Darfur.
(f) The sands, rocks and old clays of Northern deserts.

The preponderating proportion of the clay types (they include the swamps) and their distribution in terms of configuration, are to be borne in mind.

(a) The Hill and valley soils, are in elevated regions undergoing geologically rapid erosion at this moment. Not only are the parent rock masses undergoing diminution, but more rapid action can be seen on the soils of their slopes,

/e.g. Kajiko

e.g. Kajiko valley where soil "slide" is apparent which is only stopped by the evergreen vegetation of the fringing gallery forest in the valley bottoms.

(b) The red ironstone region of undulating plateaux is undergoing rapid erosion part of which is carried off in red water to the swamps, but because of contour and vegetion, erosion in this case is less rapid over most of the area than on the hill soils, though on a larger scale.

(c) The clay plains are the end products of former hill masses, locally weathered, or carried from distant areas of erosion.

(d) The great swamps are the repositories of past and present erosion in the red laterite and hill and valley soils, they occur on the White Nile where its soil-laden south western tributaries approach it. They may be found to contain also material of aeolian origin.

(e) The sands of Kordofan and Darfur are geologically recent, but not historically recent, invasions from group six in the north, they are large-grained red sands carrying a heavy vegetation for their rainfall.

(f) The sands and rocks of northern deserts. The bulk of this area is of Nubian sandstone, a rock easily weathered by comparison with the igneous rocks of inselbergs in otherwise eroded plains. Lack of rainfall reduces weathering mainly to heat fracturing, and attrition by blown sands, slower processes than that by water.

From the above outline and from the map, the large area covered by the clay plains is noticeable.

PART II - FOREST GEOGRAPHY OF THE ANGLO - EGYPTIAN SUDAN.

CHAPTER I - THE PRINCIPAL ECOLOGICAL DIVISIONS OF TREE GROWTH.

Introductory Note.

Reference is invited to plates II and I which show respectively the mean annual rainfalls, the principal soil types, and their distribution.

For the reasons which it is the purpose of this work to explain, neither of these plates separately, nor a superposition of one on the other, can provide boundaries (save only the desert edge in plate I), acceptable as the boundaries of the major ecological formations of tree vegetation. These have been shown separately in plate IV. Plate III repeats for emphasis, the three soil boundaries most significant in the forest geography namely (a) the limits of the clay plain mass through which the two Niles flow: the northern limit of this great clay plain is the edge of the Nubian Sandstone; (b) the southern limit of the sand invasion; this is a line made up of, from east to west, the valleys of the Khor Abu Habl, the Wadi Ghalla and the Bahr El Arab; (c) the limits of the major mass of surface red ironstone soils. This mass is delimited along its n.e. face by the edge of the Upper Nile and Equatoria swamp, and on its north edge by the plains of the Bahr El Arab river.

Plate IV shows the approximate boundaries of the major ecological types in mass. To maintain that such boundaries exist as hard and fast lines traceable on the ground would be to deny the facts of tree distribution. In Part II Chapter II it will be shown how individual species cross almost all of these boundaries just as individual species cross wide ranges of rainfall. But extensive areas of any one of the ecological types are seldom found outside the boundary shown on this plate as appropriate to the type in question. The versatility of species, in terms of the rainfall factor is in fact much greater than the versatility of the ecological type in which the species has its occurence axis. In the brief review of the principal ecological types which follows it has been necessary to avoid overloading the text with exhaustive lists of species and to ensure concentration on type species truly characteristic of the formations in question.

(i) Desert.

Deserts of clay soils are treeless on, and north of, the 50 mm isohyet.

/On coarse

On coarse open sand sites, *Acacia flava* (syn. *A. Ehrenbergiana*) can be taken as the ultimate arborescent surviver and occurs as far north as the 50 mm isohyet with occurences in even lower rainfalls in seasonal water courses.

Capparis decidua, *Maerua crassifolia*, and *Leptadenia spartium* are three further species of the *Acacia desert scrub* which wander over into desert on favourable sites. In certain seasons rich grass grazing known in Northern Darfur as 'gezzu' springs up within the desert boundary on the lighter soils and forms the target in those years for great northward migrations of certain Darfur camel tribes. Bagnold and Sandford (81) have written of water-course conditions in the Wadi Hawa.

(ii) *Acacia Desert Scrub.*

This stretches from the 50 mm. isohyet wet-wards (i.e. towards higher rainfall) until a line is reached at which the growth of annual grasses is such as to render annual grass fires a probability. This line occurs, on the clays and heavy loams, along the 400 mms. isohyet, and on the sands along the 250 mms. isohyet. The type species of *Acacia Desert Scrub* is the *Acacia tortilis*. With it occur *Acacia raddiana*, *Maerua crassifolia*, *Capparis decidua*, *Acacia flava* and *Boscia Senegalensis*.

In runnels within this type occur *Acacia seyal*, in well drained valley beds, *Acacia mellifera* and on low rocky hills of the Nubian Sandstone *Acacia senegal* (Jebel Lebaitor, Rufaa District and hills at Soderi, Kordofan) *Grewia tenax* and, more rarely, *Gossypium anomalum* and *G. somalense*. Sand dunes overlying the Gezira clay tongue which extends into this *Acacia Desert Scrub* zone carry *Salvadora persica*. The long sand dune known as the Goz Abu Delu, which stretches for some two hundreds of miles north and south and transects this *Acacia Desert Scrub* belt, carries *Leptadenia spartium* and over wide areas of its surface is held by *Panicum turgidum* and a *Cyperus sp.* Flat redsands west of the Wadi Mugaddam carry *Commiphora sp.* The finest growth of the scrub species in this type is achieved on the Nubian Sandstone in Khartoum Province where pure groves of *Acacia tortilis* approach woodland conditions.

Broad ill-drained basins holding water long after rains carry *Acacia arabica*. Typical riparian trees of the two Niles transecting this zone are *Acacia albida*, *Acacia seyal*, *Zizyphus Spina-Christi*, *Balanites aegyptiaca*, and occasionally *Hyphaene thebaica*, the dom palm. Towards the dry side of the zone few of these species occur under rainfall only.

(iii) *Acacia-Short-Grass-Country.*

The type *Acacia* of the *Acacia Desert Scrub* is *Acacia tortilis*. The type *Acacia* of the *Acacia-Short-Grass-Country* is the Acacia mellifera on the clay soils. On the sands however, Acacia senegal yielding the true gum arabic, occurs as a type species with the short grass although it is also a type species, with a species belt occurence, on the heavy clays on the Acacia-Tall-Grass-Country with heavier rainfall.

Referring to plate IV it will be noted that the Acacia Short Grass type is intersected by the eastern limit of the sand invasion here running along the White Nile. The ~~two halves~~ species of the Acacia Short Grass zone lie unconformably with one another at this boundary. A feature of this is shown in plate IX.

That half of the belt of Acacia Short Grass lying e.n.e. of the White Nile has Acacia mellifera as its type species; the other half to the west has Acacia senegal as the type species. But whereas the Acacia mellifera shares its section of the belt with few other trees or shrubs save Boscia sp. and Cadaba rotundifolia the sands carry, with Acacia senegal in this Acacia Short Grass Country, Albizzia amara and occasional Albizzia Aylmeri.

Commiphora sp. spreads into this sand zone from the Acacia-Desert-Scrub and Sclerocarya birrea and Combretum Hartmannianum occur, under rainfall only, as pioneers from the Mixed Deciduous Forest on these sands of the Acacia-Short-Grass-Country.

Adansonia digitata and Terminalia brownei grow in sites receiving more water than their rainfall. The type is however most widely represented by pure stands of Acacia senegal over short grass. On seasonally flooded lands near the R. Atbara which transects the Acacia Short Grass belt in the east, pure groves of the palm Hyphaene thebaica reach characteristic development and stretch down this river into the Acacia Desert Scrub belt.

Rocky hills in the Acacia-Short-Grass-Country carry many species of the Mixed Deciduous Forest of which Combretum Hartmannianum is the commonest in such sites.

On the west-ward side of the Acacia-Short-Grass-Country fires are of normal annual occurence and advance and retreat of this boundary are both common features. Wide areas of Acacia mellifera reach simultaneous maturity die out, and are burned off. Frequently they leave a bush grass formation with Cadaba rotundifolia. Occasionally large scale advances of Acacia senegal occur as, since 1939, on the Khashm El Gerba - Gedaref area. An advance towards moister conditions by Acacia mellifera has been noted in the Gefaza-Qala El Nahl area. There is no evidence of movements in either direction which can be taken as indicative of permanent advance or repeat.

Grass growth in the Acacia-Short-Grass-Country is typically knee-high, with occasional growth to waist height in favourable sites or seasons.

The principal geographical interruption within the Acacia Short-Grass-Country is the massif of Jebel Marra in Darfur which rises to 10,000 feet and carries a great variety of species described in Part III Chapter I.

(iv) Acacia-Tall-Grass-Country.

In this type grass growth exceeds that of the Mixed Deciduous Forest of wetter isohyets. The grass growth is typically five to nine feet in height and consists principally of annuals of which the commonest dominants are Adar, Annis, Anzora.

This is, above all types, the ecological formation of the heavy clay plains. Annual fires rage across the whole of this vast area interrupted only by water courses, rocky hills or areas temporarily grassless by reason of seed-failure due to lack of rain in the preceding year, or to seed-failure consequent on a long dry spell killing growth after heavy early rains have germinated all the seed in the soil. Such grassless areas are known as 'mahal'.

The type stretches on the clays across the isohyets from that of 450 mms in the region of Khashm El Girba to the Kenya border near Lake Rudolf in 800-900 mms of rainfall.

Not all of the area of tall grasses on the clays carries tree growth. The lower-lying plains, liable to flooding by rain or river, are typically treeless, tree growth being there limited to termite mounds and old river banks and mounds, and to hills piercing the swamp as at J. Teraf.

Along this axis of 700 miles only five type species share dominance on the clays. These are Acacia mellifera, Acacia fistula, Acacia senegal, Acacia seyal and Balanites aegyptiaca.

Acacia seyal is the commonest tree in the Sudan and is dominant over by far the greatest part of the Acacia-Tall-Grass-Country. Along a short axis at the north end of the type, the belts of Acacia fistula, Acacia senegal and Acacia seyal succeed one another in purity at short intervals.

Hills in this type carry a short grass growth, with reduced fire risk and carry a richer vegetation of fire-vulnerable broad-leaved species of which Lonchocarpus laxiflorus, Stereospermum kunthianum, Sterculia setigera, Anogeissus schimperi, Boswellia papyrifera, Ficus spp. and the bamboo Oxytenanthera abyssinica are frequent occurences.

/The pure

climax formations. Fire however cannot explain the absence of the

The pure stands of the *Acacias* in long grass on the plains surrounding these hills are marked contrast with the mixtures found on hills and these *Acacia* occurences pure or, with *Balanites aegyptiaca*, can only be regarded as fire broad-leaved species from naturally fire-protected sites on the clay plains, nor the absence of the *Acacias* from the hill sites.

The *Acacia-Tall-Grass-Country* is shown as including the great swamps of the Upper Nile, wet plains of papyrus and *Phragmites communis* and this appears to be their appropriate grouping. Pioneers in rising swamp (that is to say swamp the levels of which have risen by deposit) are *Acacia seyal*, *Acacia campylacantha* and, on the ridges and old river banks, *Acacia sieberiana* a species which dominates the White Nile riparian tree growth from Abu Zeid ford (where *Acacia arabica* has its sudden southern terminal natural occurence) to Kodok.

The Blue Nile and its tributaries Rahad and Dinder, as well as the Rivers Atbara and Sobat traverse this type.

The principal forest feature of the Blue Nile river is the chain of annually flooded basins carrying pure forest of *Acacia arabica* with *Crataeva adansonii* as a common undergrowth species. Meanders and ox-bow lakes on the R. Rahad are marked geographical features, with thickets of *Zizyphus Spina-Christi* on the higher levels of recent alluvium on the inner banks at bends.

In contrast with the seasonal water courses of the *Acacia Desert Scrub* and the *Acacia-Short-Grass-Country* such water courses in the *Acacia-Tall-Grass-Country* normally carry a tree vegetation poorer than that of the clay plains through which they run. In this type surfeit of water is the common cause of the treeless condition of tall-grass-land.

The principal surface interruptions of the *Acacia Tall-Grass-Country*, (apart from the swamps) are the Nuba Mountains of Southern Kordofan Province, and the Ingessana hills near the Upper Blue Nile.

In the younger valleys traversing the zone of the black and brown clays the rivers cut deeply into the clay plateaux.

Parts of the Blue Nile and Atbara rivers lie in deep valleys the Blue Nile between Roseires and Leuni; the Atbara between Meshra Akrib and a point north of Khashm el Gerba. Rain run-off from the clay plains is very restricted by the amount absorbed by the clays, by the level nature of much of the clay plateaux and by the heavy grass vegetation covering it in the season of rains and remaining until burned bare in the season of no rains.

/But from

But from clay plateaux adjacent to a deep valley there is some local run off to the river or tributary bed, and this run off, over soil carrying much lighter grass growth than that of the plateaux, has produced marked erosion in the zone in which it occurs. This is very slowly cutting back into the plateaux. The zone of erosion varies in depth (measured from the river in an inland direction) with the difference in level between the uneroded clay plateau and the drainage destination (i.e. river bed or flooded basin or tributary valley). This eroded area is known as 'Kerrib'.

There is a constancy of slope on the erosion slope where the uneroded material is a homogeneous clay plateau. The nodules and aggregates of calcium form a surface 'gravel' restricting the rate of erosion.

It is of particular significance in a study of vegetation that the features of erosion in 'kerrib' lands are not accentuated by increased rainfall. In fact the most noticeable erosion under 'kerrib' conditions is seen in the driest conditions in which the type occurs, e.g. at Khashm el Gerba. 'Kerrib' may be defined as the terrain resulting from steep run-off in deep homogeneous clay plateaux. Steep run off, in the Sudan clay plains occurs only on the banks of the R. Atbara and its two tributaries, and of the Blue Nile and its two tributaries. When it occurs with rainfalls of 600 mms. and over, the eroded surface carries a much more varied tree vegetation than the higher-lying uneroded clay plain.

On Plate V the limits of 'Kerrib' conditions are shown on the rivers on which 'Kerrib' occurs.

Where erosion of the clay plateau has proceeded down to underlying rock such occurring on the 'Kerrib' gives very marked evidences of water action e.g. the caves on the 'Kerrib' road between Hillet Haruma and Sofi on the left bank of the R. Atbara.

Erosion down to rock is seldom found in the 'Kerrib' levels but is not uncommon at river level and this indeed explains why river cutting has not gone to greater depths below the level of the badobe plateaux.

The highly carved slopes on the Upper Blue Nile, and Dinder and Atbara rivers provide sites of good drainage carrying a forest vegetation of higher moisture demand than that of the adjacent clay plain. Thus in the *Acacia mellifera* scrub but of the plains, *Acacia senegal* clothes the 'Kerrib' slopes. Where 'Kerrib' slopes are cut down into the *Acacia seyal* plain the broad-leaved *Combretum hartmannianum*, and its neighbours find sufficient moisture on the slopes. This 'kerrib' type of forest finds its highest development on the Upper Blue Nile where fine forests of the species of the *Mixed Deciduous Forest*

/reach a

reach a high development on the short slopes leading from the Acacia seyal plains down to the Acacia arabica basins on the recent alluvium of the river valley.

A common subsidiary species on the Acacia-Tall-Grass-Country is Dichrostachys glomerata which commonly forms thickets in Acacia seyal forest. On lighter soils Cannea humilis forms extensive thickets on limited areas.

A reason for including in the type Acacia-Tall-Grass-Country very wide areas of treeless tall-grass is that, in a cycle of vegetation, alternation between open grass and the Acacia-Tall-Grass condition is a common feature and has been described as the grassland-Acacia cycle (82).

The caprices of rainfall distribution producing, in some seasons and areas, the grassless condition already described as 'mahal' facilitate the establishment of Acacia thickets on open grass-lands. These even-aged thickets of Acacia in time die off leaving an open grass-parkland of Balanites aegyptiaca.

This phase may develop to treeless grassland or to Acacia forest. There is a tendency for increase in Acacia senegal under living Acacia seyal and towards increase of Acacia mellifera under living Acacia senegal.

In brief, a species of higher moisture demand tends to follow the die-out of an even-aged stand of a species or to become established on treeless grass-land, whereas a species of lower moisture demand tends to invade the living stands, but seldom survives the death of the nurse species and the intensified fires which follow its disappearance. To summarize the vast pure stands of Acacia seyal growing on rich dark cracking clays form the principal feature of Acacia-Tall-Grass-Country. These rich soils produce in cultivation heavy crops of sorghum millets and of sesame and represent an agricultural asset of the highest importance to the country and of no little importance as future sources of a grain for certain world markets.

(v) Mixed Deciduous Fire-Swept Forest.

On the wet side of the great belts of the gregarious Acacias, under broader leaves, grass growth is to some degree reduced. The improved rainfall, and the slight decrease in the severity of fires (due alike to the lighter grass growth and the shorter dry season) give scope to a great variety of broad-leaved species giving, for some six months of the year, a shade-casting wood-land of very varying specific composition but of surprisingly little variation in type.

/This wood-land

This wood-land reaches its highest development on the red ironstone or laterite soils of the extreme south-west where it extends over approximately 100,000 square miles of lightly populated country (Plate IV). It is broken only by small hills and by the narrow riparian swamps of the tributaries of the Bahr El Ghazal and Bahr El Arab. Many of the species of the Mixed Deciduous Forest of the red ironstone occur in two other areas.

They stretch north of the Bahr El Arab on to the southern parts of the sand invasion in Western Kordofan and Southern Darfur and they occur in a fringe of broken country along the Abyssinian frontier from the R. Setit to the banks of the Upper Akobo River.

Species of the mixed deciduous forest found in this sand occurence in Darfur are :-

Tamarindus indica.
Anogeissus schimperi.
Bauhinia reticulata.
Sclerocarya birrea.
Albizzia zygia.
Detarium senegalensis.
Adenium honghel.
Diospyros mespiliformis.
Acacia campylacantha.

In their sand occurence they mingle with Albizzia anthelmintica, Albizzia amara, Dalbergia melanoxylon and Acacia hebecladoides (syn. A. sp. near reficiens) and reason could be found in support of including this area with the Acacia-tall-grass-country or even for classifying it as Albizzia bush. For reasons of the absence of the purity which characterizes the Acacia-tall-grass belts and because of the occurence (and importance in the area) of these species typical of the Mixed Deciduous Forest the proper grouping of this part of the sand area seems to be with Mixed Deciduous Forest.

While many notable species typical of the Mixed Deciduous Forest of the laterite are absentees from the Abyssinian frontier fringe, its proper classification is without doubt also with the Mixed Deciduous Forest.

The three groups of the Mixed Deciduous Fire-Swept Forest thus become :-

(a) Laterite or red ironstone type.
(b) Sand type.
(c) Foothill type.

(a) Laterite or Red Ironstone type.

The principal characteristics of this type are a grass growth reduced by shade but not to the point of stopping grass fires, great variation in composition, of tree growth, with a discernible zoning of the dominants across the isohyets to be described in Part II Chapter II, and thirdly t-rmi-te influence not only on the soil properties and the nitrogen cycle but on the whole composition of the forest.

In place of the great areas of pure annual grasses typical of Acacia-Tall-Grass-Country the forest floor carries a high proportion of perennial grasses which sprout afresh immediately after fires and offer some cover to the soil in the ensuing early rains. A vernal aspect vegetation forms a further contribution to the soil cover in the early rains substituting the soil-protected bulb and tuber for the thick seed-coat and the hygroscopic seed-burying awns of the annual grasses as the means of evading extinction by fire.

The moisture equivalent of these red laterite soils is high. The run-off is also high in localised areas because of the undulating nature of the country and because in places it has been eroded to form 'safai' a bare area with the hard gibbsite layer exposed at the soil surface. But rainfall on the red ironstone soil is always more effective than equal precipitation on clay plains, and sometimes more effective than a heavier rainfall on heavy loams of the Frontier uplands e.g. the Yei area.

A measure of the efficacy of forest vegetation in reducing run-off is available by using figures from Hurst & Phillips (42 p. 90).

The area of the Jur River basin is 49,000 sq. kilometres. The mean annual rainfall is 1,200 mms. The precipitation on the basin is 59,800 millions of cubic metres. The discharge of the Jur is 4,780 millions of cubic metres or 8% only of the total rainfall.

In composition this vast area of 100,000 square miles of forest contains so many combinations of so relatively few species that short and concise description must confine itself to the essential features.

The one species which is remarkable in being gregarious in occurence over wide areas is Isoberlinia doka.

Uapaca sp. occurs with Isoberlinia sp. only at the wettest end of the type. In this mixture it may later be confirmed that Isoberlinia dalzielii is the common species.

Anogeissus schimperi also occurs gregariously, and in that condition, on favourable soils, appears to be the species best fitted to produce grassless forest and thus another ecological type namely Transitional Forest (see vi).

/The large

The large dominants of the Mixed Deciduous Forest are Khaya senegalensis, Anogeissus schimperi, Afzelia africana Erythrophlaeum guineense, Lannea velutina, Burkea africana, Prosopis oblonga, Amblygonocarpus sp., Sclerocarya birrea, Parkia oliveri, Mimusops schimperi, Pterocarpus lucens, Cordyla sp. Butyrospermum niloticum, Vitex cuneata.

Thickets of Strychnos spinosa are common towards the wet side of the formation.

There is scarcely a woody species of the whole 100,000 sq. miles which is not, with time and patience, found somewhere in the type to be dominant over an area however small.

An essential feature of the forest of the laterite is that dominance is localised. When this has been realized the fatuity becomes apparent of attempts ecologically to subdivide the mass on any criteria other than those of soil and water.

On the laterite proper, the forest quality can by no means be assumed to improve with improving rainfall. For instance a very high type occurs with pure Anogeissus schimperi and evergreen shrub undergrowth round Tali on the dry side of the 1000 mm isohyet.

The quality of laterite forests depends less on the identity or distribution of the dominants, than on the degree to which evergreen shrubs succeed in their shade.

The soil-holding power of the vegetation is greatest where the evergreens thrive.

Slope and run-off also govern quality but the effect of slope can be completely outbalanced by a heavy undergrowth of these shrubs.

The highest type of Mixed Deciduous Forest on the laterite occurs on escarpments and declivities where a valley has cut down through several horizons of the laterite "measures".

Some of these strata are much less permeable by water than others and induce a flow along their own horizons to form springs on the base of the valley section. In such sites are found relics of Closed Lowland Forest which from other sites has retreated 150 miles to the South. Examples are Chlorophora excelsa near Cleveland mission, at Duniaksi valley (Busseries left bank) and near Lui, Mimusops Kummel and Antiaris toxicaria on Busseries scarps, and Isoberlinia doka on slopes in its more northern occurence. The most widely prevalent of all species on the laterite is Anogeissus schimperi.

Landolphia Florida is a common climber.

/It cannot

It cannot be emphasized too strongly that the Mixed Deciduous Fire-swept Forest presents remarkable constancy and conformity considered as a type. As a type it is virtually static and will remain so as long as fires sweep it. Within this constant type there can be great variation in specific composition.

Neither its components nor their proportions in the constitution of the forest are constant over more than very limited areas measurable in acres. Aevaudin has noted similar conditions in the West African Closed Forest (83)

The search for dominants revealed a stratification or belting of species across the isohyets certainly less obvious than in the pure Acacia stands of Acacia-Tall-Grass-Country but no less certain, and the species belts of the Mixed Deciduous Forest are described hereafter in Part II Chapter II. A (ii).

The third of the principal characteristics of the Mixed Deciduous, termite influence, is exerted on so vast a scale as virtually to govern the specific composition of the forest.

Chevalier first called attention to the influence exerted by Tamarindus indica as a shade-caster typically occurring on a termite mound. Over very vast areas the whole Mixed Deciduous Forest can be analysed into a series of tree colonies each centred on a mound, which spread out towards one another and meet along a honey-comb pattern.

While Tamarindus indica is the mound type species whose grass-suppressing effects make the fire protection process most obvious, the great majority of tree species of the type exert, when given the opportunity, a similar nurse influence when growing on or near a mound.

The mounds of the honey-comb are not all new and high. More frequently they are old and flattened so as to be no more than a foot in height above the common level. But even as such they form the true units of soil surface and of the growing stock and no planting scheme for the Mixed Deciduous Forest can overlook this fact.

There is no humus layer, termites convert the newly fallen leaves to their own ends, and within a matter of months the fallen leaf is converted and only the red regurgitated clay moulds remain.

The principal geographical interruptions of the Mixed Deciduous are the grass plains known as 'toiches' which border the rivers penetrating this forest and are treeless (or carry a much modified tree growth) because of seasonal flooding when the rivers rise during the rains. These grasslands run in narrowing tongues from the great swamps into the heart of the Mixed

/Deciduous Forest

Deciduous Forest until they disappear when the slope up to the continental rift - the Nile-Congo Divide-increases and the valleys narrow. Fringing or gallery forest then covers these upper narrowing valleys (see vii).

At first this is of a wet-floor type with *Mitragyne stipulosa*, *Cola cordifolia*, *Syzygium owariense*, *Pycnanthus kombo*, *Erythrophlaeum guineese*, *Sarcocephalus esculentus*.

The upper levels of these flood plains (toich) areas carry *Bauhinia reticulata*, *Gardenia lutea*, *Pseudocedrela kotschyi* and *Mitragyne inermis* all of which frequently occur gregariously.

On these areas also various species of *Combretum* and *Terminalia* are common and tall dominants are *Borassus aethiopium* and *Daniellia thurifera* (syn. *Paradaniellia sp.*)

Contour interruptions are ironstone ridges and plateaux which protrude in places from the gently undulating terrain and influence the composition but do not form interruptions in the type. On these hard slopes tree growth is often improved. Inselbergs and monadknocs of basic rocks protrude in increasing frequency towards the south-western limits of the *Mixed Deciduous* carrying great profusion of species including many *Ficus spp*.

Riparian vegetation on the upper reaches of the rivers transecting the *Mixed Deciduous* e.g. Jueh and Busseries, includes *Irvingia Smithii*, *Daniellia oliveri*, *Kigelia aethiopica* on the river bank, leading inland through a Terminalia belt on flood plain to *Anogeissus schimperi*.

Inroads by man on the *Mixed Deciduous* for purpose of cultivation leave a much more serious mark than anything done by man on the clay plains.

The *Mixed Deciduous* of the laterite is scarred by 'hobai', which are areas of secondary growth marking abandoned cultivation clearings. In places these have developed to the hard bare patches, or 'safai' already described. More commonly they have been reclothed by secondary growth before their soil has been wholly removed, and have begun the long slow progress back to forest. Common species in this secondary growth are *Grewia mollis*, *Annona senegalensis*, *Hymenocardia acida*, *Bridelia micrantha*, *Entada sudanica*, *Parinari curatellifolia* with *Combretum* and *Terminalia* species.

There is neither ebb nor flow of the *Mixed Deciduous Forest* type to be noted on a large scale along its boundaries save where man has been active in cultivation. There is continuous internal specific change within the type but this is neither pronouncedly wet-wards nor noticeably dry-wards over any extensive area.

/vi. Mixed

vi. Mixed Deciduous Grassless Transitional Forest.

An essential characteristic of the great masses of Mixed Deciduous Forest is that the grass growth is burned, save for accidents, annually.

It is necessary therefore to give particular note to areas within the Mixed Deciduous Fire-swept formation in which grass suppression has been achieved. In the fire-swept type the chief regeneration hazard is the degree of intensity of the annual fires.

The nurse Tamarindus (with several other genera) on its termite mound achieves grass suppression and hence forms a temporarily fire free nursery for other species. But these sites are nuclei scattered over the area. Continuous areas exist in which grass has been suppressed by evergreen under-shrubs, species which have not yet been fully studied but which include Rhus sp. and a dwarf Mimusops sp. Anogeissus schimperi is the species most commonly found as the dominant over this fire-suppressing undergrowth. Here this tree species is commonly gregarious. Areas of this type around Tali and on the upper Lummatinna are of great significance as forming the closest approach to closed forest found under rainfall only in the Mixed Deciduous formation.

vii. Closed Lowland Forest, including Fringing or Gallery Forest.

This type is poorly represented in the Sudan if the criterion is proportion of the total forest area.

There is little extent of country which can be classified in this type,

apart from the long rope-like strips of closed forest which follow the running surface water from springs rising along the Sudan's frontier with the Congo in Western Equatoria down through the Mixed Deciduous Forest until the surface water level falls, and along streams rising in the Imatong, Acholi, Dongotono, and other mountain groups in eastern Equatoria.

Exceptions are three very fine forests of limited extent closely resembling the "bowl" forests of Uganda and covering some fifteen square miles at Laboni and Lotti in Eastern Equatoria and at Azza in the Maridi area of Western Equatoria. A fourth has been reported to have been seen from the air between Yei and Maridi. The distribution of 'bowl' forests is shown in Plate VI.

Tallanga, a foot-hill forest of the Imatongs, since it cannot on its specific composition be included with mountain forest, is meantime included in the Closed Lowland type though further examination and comparison may show it to merit distinctive

/treatment on

treatment on account of specific differences from all others. It is indeed possibly a significant relic of wetter times when there was closer continuity between the ecological regimes of the Sudan and West Africa.

In Azza and Lotti Mildbraediodendron excelsum, Funtumia elastica, Ceiba pentandra and Chlorophora excelsa are type species, and Coffea robusta is a common under-shrub.

These forests bear evidence of recent retreat of forest on their fringes and have now been protected by firelines.

In Tallanga a much greater variety accompanies Chlorophora excelsa including Chrysophyllum spp., including albicum Ochrebra macrantha, Entandrophragma sp., Alstonia congensis many unidentified Ficus spp. with Maesopsis eminii forming very fine boles.

The fringing or gallery forests are found in their highest development along the south western frontier and contain a great variety of species. Their valleys widen and become more shallow and flatter-bottomed with distance from the frontier. Khaya grandifoliola, Canarium schweinfurthii, Ceiba pentandra, Erythrina sp. of the upper valleys are replaced by Mitragyne stipulosa, Cola cordifolia, Erythrophlaem guineese, Pycnanthus kombo, and Sarcocephalus esculentus of the ill-drained broader valleys. Still nearer the broad grassy valley Mitragyne inermis replaces M. stipulosa.

This type eventually is replaced in lower rainfall and on less reliable water courses by Anogeissus schimperi and Acacia campylacantha on the valleys in the laterite around Yau.

These fringing or gallery forests are, typically, dependent on a water-supply additional to that of their rainfall. Where this takes the form of clear streams arising from springs and running in well drained but narrow valley beds the trees reach 200' in height. Where drainage becomes seriously impeded by contour, forest growth is replaced by open grass-land known as 'toich'.

Along the 150 miles which separates the well-drained valleys at frontier from the open 'toich', a rapid succession of species is to be found occupying the valley bottom. Downstream the type is destroyed in the main valleys by surfeit of water. Where this occurs the type can still be found in the better drained tributary valleys. Knee roots are common in certain of the species of the ill-drained valleys towards the downstream limits of fringing forest. It is not improbable that the bowl forests of Azza, Lotti and Laboni owe their existence to an underground water supply in excess of their rainfall holard. It is certain that Tallanga, a foot-hill forest, benefits by a subsoil water supply derived from the bare rock catchments

/above it,

above it, which drain in part to streams running through the forest and in part downwards through its soils. It cannot be said of the forests of this type that they are the product of the rainfall receipt of their own soils and of no other moisture.

Certain species of the Mixed Deciduous Fire Swept forest are found making so much better growth in the Fringing Forests as to have led to varietal distinction having been made between the tree of the Mixed Deciduous Forest and what is probably the same species on water favourable sites in Fringing Forest. In other cases, e.g. Sarcocephalus esculentus, the difference in vegetative growth is just as marked but identity is yet undoubted. These twin occurences are a promising subject for the study of polymorphism. Examples occur in the genera Isoberlinia (doka and angolensis spp.), Parkia (oliveri and filicoidea spp.) Lophira, Erythrina and others.

(viii) Mountain or Cloud Forest.

As will be shown later there is always a striking difference between the tree growth of the plain and of the hill-side in any rainfall. But the term Mountain or Cloud Forest is here restricted to closed grassless high forest occurring above five thousand feet in certain mountain ranges in the south eastern Sudan. These ranges are the Imatong-Acholi range near Torit (Mount Kinyeti 10,000 feet) the Dongotona hills, to the northeast thereof, the smaller Didinga hill group at Nagichot and one or two smaller groups towards the Abyssinian frontier. These hills lie between the 800 mm and 1000 mm isohyets as determined by adjoining meteorological stations on the plains.

Reliable records of rainfall at the higher levels have not yet been made so that it is not yet possible to corelate mountain forest growth with rainfall. The eastern slopes are less well-forested than the western.

The largest area of mountain forest is that on the Imatong-Acholi group a description of which was given by Chipp (13). This is now known to cover about 200 square miles. The change from fire swept hill side carrying Protea abyssinica, Acacia abyssinica, Erythrina sp. tomentosa and Faurea speciosa is abrupt. There is no sign of retreat traceable apart from limited damage by man.

Dombeya bucale, Hagenia anthelmintica, Pteris aquilina and Rubus sp. (Blackberry), in places form a grass-reducing fire cushion between the forest, which rises in a vertical wall, and the fire-swept mountain-grass-land. The two first named are pioneers in advance of the forest into grass-land. Forest stretches from 6000' to a level close to 10,000'.

Podocarpus milanjianus occurs from 6000' upwards. P. gracilior is not reported from the Imatong although reported from

/Dongotona.

Dongotono. Where introduced it bears evidence of its ability to succeed below 5000'. *Acacia mollissima* and *Juniperus procera* have been successfully introduced at 6500', the former on grassland and the latter after *Podocarpus milanjianus*. The lowest hill forest contains much *Albizzia probably marunguensis* which appears to be the most successful colonist of the spaces left by natural fall of the old trees of other species.

With *P. milanjianus* occur *Olea Welwitschii*, *Fagara sp.* At 8000' giant bamboo is common without reaching the purity or extent of its occurrence in Kenya forests.

It is notable that species common to this forest and to the forests of the Kenya highlands tend to occur about 1000' lower on these Sudan mountains than in Kenya as if altitude were in some way offset by latitude. The factor here cannot be temperature since considerably higher mean temperatures prevail in the Sudan than at the same heights in Kenya.

These limited mountain forests of the South eastern Sudan are obviously outliers (on the only suitable altitudes) of the forest vegetation of the East African and Abyssinian Highlands deserving of analytical comparison with the composition of the hill forests of, say, Marsabit in Kenya. So far as is known they are, for most of the species which compose them, a north-eastern limit. If the mountain chain of the eastern Africa be regarded as a plant highway (Bews. 1.) a side road at one time must have existed as far from the main mountain line as the Imatong-Acholi. *Olea chrysophylla* has penetrated even further west to Jebel Marra in the western Sudan. *Protea* has carried its generic if not its specific banner west of the Nile. But no other Sudan occurrence is known of other type species of this mountain forest type. *Juniperus procera* has not been found in these mountains. This species has failed to cross the gap (or failed to survive having crossed it) between the main mountain road and these outlying mountains. But *J. procera* occurs on the Red Sea Hills where they cross the Eritrean-Sudan frontier in latitude 18° N. on an isohyet of only 200 mms. Plate VI.

This site however is on the main mountain highway. *J. procera* is common at 8000' on the Eritrean mountain line occurring with species such as *Syzygium guineense* and several other species common on the plains *Mixed Deciduous Forest* of Equatoria. *Stegonotaenia araliacea* which is common in the East African Highlands and frequent in the Sudan west of the Nile, having a northern limit on J. Daier, is apparently absent or very rare on these south-eastern mountains. Although they have not here been accorded the status of a principal ecological division it should be noted that *Rhizophora sp.* and *Avicennia sp.* occur in dwarfed form on the Red Sea Coast.

This concludes the review of the principal ecological sub-divisions of tree growth in the Sudan. These types are more constant than their species composition.

PART II - CHAPTER II - THE PRINCIPAL GEO-PHYSICAL INFLUENCES IN SPECIES DISTRIBUTION.

A. Isohyetic zonation of species in zones or belts directly reflecting rainfall.

(i) Species belts of the **Acac**ias country.

In the preceding chapter it has been shown that Acacia tortilis, Acacia mellifera with Acacia senegal, and Acacia seyal are the type species dominating three of the principal ecological formations. But not one of these three species is confined in its distribution to the ecological formation in which it is a dominant. Yet in passing from the desert edge to the 1000 mms. isohyet and considering only occurences on datum soils (which receive no more moisture than their rainfall and lose none of it by run-off), zonation of Acacia spp. according to rainfall is at once apparent.

In the experience of the writer (quoted in part by Malcolm 46(a), the order of occurence on such sites, beginning at the desert edge and proceeding wet-wards, is :

	100 mms.	Acacia flava.
		Acacia orfota.
		Acacia tortilis.
		Acacia raddiana.
	200 mms.	Acacia mellifera.
All on		Syn. A. spirocarpa.
datum		Acacia fistula.
clays.		Syn. A. seyal var. fistula.
		Syn. A. verek.
		Acacia senegal.
		Acacia seyal.
		Acacia drepanolobium.
		Acacia campylacantha.
		Syn. A. suma.
		Acacia Sieberiana.
		Syn. A. verugera.
		Acacia albida.
		Acacia hebecladoides.
		Acacia stenocarpa.var.multijuga.
	1200 mms.	Acacia abyssinica.

Sudan This sequence is best seen along a N-S axis in the Eastern stretching from the River Atbara to the River Sobat (Plate VII).

This sequence covers a rainfall space of 1000 mms. between the 200 mms. and the 1200 mms. isohyets, and a distance of 500 miles.

/This axis

This axis crosses the isohyets obliquely. On a foreshortened axis (plate VII) crossing the isohyets more nearly at right angles the same species series occurs on datum soils along a shorter line, less the last three species.

These Acacia belts are characterised by wide areas in which each species in turn occurs gregariously and the medial axes of these gregarious belts are, in this work, referred to as the species belt axes. Wet-wards and dry-wards of each belt axis there is mixing with the wet, and with the dry, neighbouring species respectively.

The emphasis, in the Acacias country, is on the fact that they do occur gregariously on wide expanses of datum soils and that on these soils there are narrow differences in the rainfalls appropriate to each species.

(ii) Species belts in the Mixed Deciduous Forest.

The determination of species belts in the vast area of the Mixed Deciduous Forest is not so simple a matter. The very large number of species making up this ecological type, the shorter rainfall span (300 mms. between the 1100 mms and the 1400 mms isohyets) and the shorter axis (300 miles from Aweil to Yambio), are factors obscuring zonation of species. A further factor is that gregarious occurence is rare in the species of the mixed deciduous forest with exceptions in the cases of only a few species of which the most pronounced are Isoberlinia doka and Anogeissus schimperi.

Nevertheless there is clearly distinguishable along any axis crossing the isohyets, a regular order of occurence of type species, as dominants if not gregariously, in the Mixed Deciduous Fire swept forest. Beginning from the 1050 mms isohyet this order has been observed by the writer to be, on datum soils :-

1050 mms	Acacia hebecladoides	(on the wet edge of the Acacia Tall Grass and penetrating the Mixed Deciduous.)
On red ironstone soils	Sterculia setigera	
	Khaya senegalensis	
	Isoberlinia doka	
	Afzelia africana	
	Parkia oliveri	
	Vitex cuneata	
	Prosopis africana	
	Albizzia zygia	
	Amblygonocarpus obtusangulus	
	Anogeissus schimperi	
	Pterocarpus lucens	

/Butyrospermum

	(Butyrospermum niloticum
	([illegible] Kunmel
On red	(Lophira [illegible] *Lophira alata*
ironstone	(Monotes kerstingii
soils	(Strychnos spinosa
	(Crossopteryx febrifuga
1400 mms	(Erythrophleum guineense
see Plate(VIII)	

The Combretaceae, Combretum spp. and Terminalia spp. are so frequently secondary in occurence as to render them unsuitable as types in the study of tree distribution undisturbed by man.

B. Major interruptions obscuring isohyetic zonation of species in rainfall species belts.

(i) Surface Soil Texture.

Earlier in this chapter the Acacia belt sequence was given for the Atbara - Sobat axis.

This axis runs entirely over clay soils of clay content rising steadily southwards from 30% clays in the north to 80% clays in the south. The special significance of clay content in datum soils is treated in detail in Part III of this work.

But the most striking and elementary fact in the distribution of Sudan trees taking the country as a whole is that the tree species which require 3 x X inches of rain on clay soils require less than 2 x X inches of rain on sands.

The most prominent example of this is seen in the distribution of Acacia senegal the gum arabic of commerce which is so important an item of Sudan trade. This species has two belt axes, one along the 450 mms isohyet on the sands of the western Sudan and another along the 650 mms isohyet on the dark cracking clay soils of the eastern Sudan. This is shown in Plate IX.

Acacia mellifera and Acacia seyal as indeed all species, exhibit similar change in rainfall requirement with this change in soil.

The result is, to borrow from geology, unconformity in species distribution most marked along the boundary between the continental sand and the vast clay plains.

Reference to the soil map (Plate I) will reveal that save for the ironstone region of the south west, the hill and foot hill groups, and the Nubian sandstone, most of the country lies under a blanket of sand or of clay.

/The northern

The northern origin of the sand is established. The dispute as to whether the clay plains are aeolian or alluvial continues.

For the purposes of this work the origin of the materials out of which the clay soils have been made into their present state is of less importance than the climatic factors which have made them what they are today.

The boundaries between sand and clay are species boundaries in any given rainfall. Apart from the continental sand blanket, there are minor areas of local sand originating from river beds, and inland deltas.

These local sands carry species of higher moisture demand, usually markedly different from the species of surrounding soils.

(ii) Contour.

Violent but local changes of vegetation are found wherever the plains of sand or of clay are pierced by inselbergs, monadnocks and outcropping rock. The change in vegetation is more marked where these pierce the clay plains than where they pierce the sands.

Equally marked is the change in tree vegetation where the plains are cut by rivers and seasonal streams or are flooded by their waters to form seasonal swamps or inland deltas.

In the study of tree distribution it is important to regard all of these as interruptions of the otherwise prevalent pene-plain condition. So regarded, they are sites carrying a vegetation whose differences from the vegetation of the plains is the significant subject for study and interpretation.

CHAPTER III. The Analysis of Species Distribution Records by Transects.

A. Instances of apparently anomalous distribution.

In the preceding chapter reference has been made to the prominent anomaly in species distribution which is so noticeable on the border lines between the continental sand and the great clay plains, namely unconformity in the Acacia belts. This is the most obvious apparent anomaly and is outstanding evidence that rainfall is more efficiently used by the perennial plant on the sands than on the clays.

/It has been

It has been shown in Part II Chapter II that particularly the Acacias and less obviously the type species of the Mixed Deciduous forest succeed one another on datum soils in a definite order with increases in rainfall.

These are the belt occurrences of species and their medial lines are species belt axes. Consideration must now be given to the occurrence records of these and other species outside their belt occurrences. The belt occurrences are on datum soils. A study of their occurrence on sites other than datum soils has been made for the commonest Acacia spp. and for certain of the species of the Mixed Deciduous Forest.

Acacia senegal, which we have seen to have a belt occurrence on sands and another in higher rainfall on clays occurs on non-datum sites in rainfalls far outside the rainfalls of either of these belts. Its rainfall factor span on non-datum sites is from 1400 mms, on sheet erosion slopes at Yambio to 300 mms. on hill sides in N. Kordofan and Dufea District.

In both these extremes it is closely accompanied by Acacia mellifera its near neighbour in their belt occurrence. Anogeissus senegalensis of the Mixed Deciduous (Laterite type) (1100 mms. at Wau) occurs on the banks of seasonal streams in Darfur in 500 mms. of rainfall.

Sterculia setigera with a datum soil occurrence in 1200 mms. is common on the rocky hill sides of Kassala in 300 mms.

Acacia fistula with a belt rainfall requirement of 500 mms in Kassala Province, colonizes certain seasonal swamps in Upper Nile Province in twice that rainfall. It is the Acacias of the 400 – 500 mms rainfall belts on datum soils which are the only successful species on short season swamps in 1000 mms. of rain. This has been confirmed by afforestation work in which the longer the seasonal inundation the 'drier' the Acacia species required for successful plantation.

Acacia tortilis, with extreme occurrences in seasonal runnels in 50 mms. rainfall on the desert edge, occurs on datum sands in 150 mms. near Khartoum, on clays in 300 mms. in Kassala District and in 500 mms. on the erosion slopes of central Butana hill-sides. While not properly a forest species the wild cotton, Gossypium anomalum should be recorded here as exhibiting the same phenomena. It thrives and perennates on a bare almost soil-less rocky hill top at Omdurman in 150 mms and at Jebel Kurgul in Kordofan occurs on shallow flood sites in over 400 mms. of rainfall. In both sites it occurs with Grewia tenax.

To include a monocotyledon in the picture, Hyphaene thebaica occurs on runnels and on seasonally flooded well-drained

soils close

soils close to the river in Atbara area, in 100 mms; on red loams in Gedaref in 600 mms; on ridges of loam in 750 mms in Upper Nile Province, and on cotton clays in Roseires in 900 mms.

Its occurrence on datum sands has not been noted, but is to be sought in Western Darfur where the continental sand crosses the 600 mms. isohyet.

Carissa edulis has a span which stretches from the flood plains of Dinka country to the Red Sea hill tops; from 600 mms. to 200 mms. This species has local names in half dozen languages from Beja almost to Bantu.

In the parallel sand-dune country of northern and eastern Kordofan where long fixed dunes run north and south for many miles, the sandy dune tops carries a more mesophytic vegetation than the loams and light clays of the hollows between the dunes. The more xerophytic types are in the hollows even although these hollows are subject to shallow flooding in the rains.

One of the most southerly occurences of a species is typically in a so-called 'wet' hollow, and the most northerly occurence on the light sands of a dune crest or on a rocky hill.

Examples are :-

Albizzia aylmeri on dune clays with 500 mms. of rainfall and on a dune top along the Bara - Nahud road with less than 300 mms. of rainfall.

Terminalia brownei on our river flood plains with 800 mms of rain besides seasonal flood water, secondly on sands in [illegible] with 500 mms and in rocky valleys on Jebel [illegible] with 400 mms.

In the Eastern Sudan in the wetter parts of the broad Acacia seyal belt, (800 mms) the species growing on the ill-defined beds of slow water-courses which wind from distant catchment areas through the clay plains is Acacia fistula requiring only 400 mms in its belt occurence, but here growing on 800 mms, plus the seasonal flushes of the water-course. Round the bases of the plinths of inselbergs where plinth run-off spills on to, and floods, the immediately surrounding plains of dark cracking clay ("cotton soils") carrying Acacia seyal, the species inhabiting the flooded soils is Acacia fistula. See Plate X.

Examples occur on the Roseires - [illegible] road, and around the hills of Southern Gedaref.

Drainage hollows in the red ironstone or laterite country with the Mixed Deciduous Forest cover described in Part II chapter I (v) carry a much more xerophytic vegetation

/than the

than the ironstone slopes draining down to them even although these have a comparatively heavy run-off.

Apparently anomalous occurrences are not confined to trees. It is with hesitation that the vast subject of grasses distribution is introduced but mention must be made of several striking instances in which grasses exhibit the same distribution phenomena.

Saccharum biflorum occurs on 70% clays at [illegible], in Upper Nile Province in 700 mms. of rain to which is added annual flood.

It is a common species on sands in the dry western desert of Egypt.

Panicum repens exhibits the same behaviour. Bews (p. 251-256) has drawn attention to the varying habit of several grasses including Panicum repens and writes "some hygrophilous species e.g. Paspalidium geminatum,* Panicum repens etc. actually on occasions become psammophilous growing through sand and becoming modified in the process, but not specifically distinct".

Bews also records (p. 275) "Imperata cylindrica another species which is often psammophilous". This grass is common on heavy loams in 1400 mms of rainfall in Yambio District of Equatoria but remains to be recorded on the sands of lower rain isohyets.

Xerophily, hygrophily and psammophily as plant attributes tend to become meaningless when so many species can exhibit all three and when a marsh, a clay plain in 900 mms of rainfall, and a sand-dune in 300 mms are found to be equiconditional sites in terms of chresard, judged by the success of individual species colonizing all three.

* Paspalidium geminatum.

PART II - CHAPTER III B.

B. Distribution Transects.

From the distribution records made by the writer in the Sudan, it is apparent that no tree species, save possibly the Herminiera elaphroxylon of the swamps, is so restricted in its range as to be confined to any one soil, or even to any one major soil group in the chemical groups of soils.

It is in consequence not possible to find tree species indicators of the chemical groups (and many disappointments have followed attempts so to do) save under strictly limited physical conditions of rainfall, of surface, and of site.

Those over-riding physical conditions which make pedocals into sites favourable also to the species called those of the pedalfers, and vice-versa, become primary objects for study.

These physical conditions are the factors directly governing the natural distribution of tree species in the dry tropics and it is a simpler matter in these dry tropics to find constant plant indicators of particular physical conditions, than to find any indicator of a chemical soil type. As a factor in distribution, the soil nature, in chemical classification terms, is a factor sub-ordinate to the physical conditions, in dry tropical regions where thirst occupies so predominant a place in the government of plant life.

The predominance of the purely physical factors, indeed, may be masked by chemical factors in countries where perennial water is abundant, but nothing masks it in these countries where the sun makes such an inexorable demand on the surface of leaf and of soil, and where the rare clouds contribute so little to the satisfaction of this demand or to its mitigation. In such areas the water relation is the paramount relation.

A perennial plant, under circumscribed physical conditions may be used as the indicator of the chemical conditions suited to another plant of which it is the proven and persistent associate, but it cannot, in dry tropical practise, be used as an indicator of a particular soil type, nor of a particular rainfall save under very great restrictions of area and of surface condition. These restrictions are so severe as to make plants valueless as indicators of chemical soil types save under what may be called micro-conditions of extent. Indicator plants may be useful on, say, one man's holding for comparison with that of a neighbour on similar soil, but they cannot be used for the same purpose over many square miles, and they have the most limited value over districts let alone provinces.

In the studies summarized here, it has been found that no such tree species is restricted to any one soil or even to any one of the major chemical groups of soils. However conclusive the evidence obtainable, by work restricted to a single district, that a particular species sp. is the certain indicator of the black cracking peroosals, a study over wider areas and other rainfalls will in every single case reveal that, under surface physical conditions, this same species is in another area confined to soils of utterly different chemical groups. Such other occurrences are not accidental, but equally typical of their rainfall soil and surface conditions.

In the dry tropics, in any evaluation of the 'fertility' or better, of the growth value of sites, the first and elementary sub-division of sites is not on a chemical basis but on the basis of their moisture receipt and disposal.

Are they sites receiving rainfall only, or does water flow on to them above the surface or beneath it?

Do they hold all the rain they get or does a part of their rain receipt flow away from them, or stand on their surface until evaporated into the dry tropical air?

How does the extra receipt in the one case and the partial loss in the other, affect the soils themselves and how is it reflected in the vegetation they carry?

In classifying and considering dry tropical soils on this basis it is to be noted that the surfaces in receipt of rainfall only, and losing none of it by run-off, are the datum sites in the study of each particular rainfall district. All datum sites are characterized by the absence alike, of flow off their surfaces and of flow on to their surfaces. Water does not, in normal seasons, drain off their surfaces on to adjoining land surfaces, not yet by way of water courses, into distant rivers or less distant pools and land-locked lakes. Nor do datum sites receive flow. more, or retain less than their appropriate rainfall are sites divergent

As will be further discussed in Part III Chapter I, the areas in the same one district which receives divergent, in one direction or the other, from the datum site for the rainfall, and so carry a vegetation which cannot directly be corelated with the rainfall which it receives. The datum soil of one rainfall district does not carry the same species as the datum soil of another.

But the species of the datum sites in one district are invariably to be found also on divergent sites in adjoining, as well as in distant, rainfall districts.

/If it

If it should ever prove possible to corelate, in chemical terms, the conditions in which one single species can occur on datum and on divergent sites, this will only be done long after the earlier corelation of these sites on physical terms. The present work is a contribution to corelation of occurence sites on physical bases.

In the Sudan, datum sites are usually plains, but where soil surfaces are coarse sands datum sites may be undulating and even dune sites.

In certain limited areas, overlying and derived from basalts, clay soils are in such balanced relationship with their rainfall that, even where clays cover rolling low hills or high mountain sites they constitute datum sites, having no loss by run-off.

Datum sites carry that vegetation which must be held to be the type vegetation for the rainfall in question, since no other sites in that rainfall carry a vegetation which is the product of the whole of their appropriate rainfall and of no other water. While the datum plains are usually clay soils, and clay plains are apparently the ultimate end product in all soil development in the seasonally dry tropics of North Africa, yet sands also absorb their rainfall and such sites are found to differ very greatly indeed, in their vegetation, from datum clays absorbing the same rainfall. Attention has been called in an earlier chapter to 'unconformity' along the clay-sand frontier.

Even within the one class of sites which are taken as datum sites in terms of their disposal of their rainfall receipt, namely sites whose soils absorb their rainfall and no other moisture, further subdivision is necessary, and here also the subdivision is on a physical basis, a basis again strictly tied to the water relation. It is, in fact, a subdivision on the basis of soil particle size; on the basis, that is to say, of clay content.

Examinations of the records made show that a species does not indicate a particular rainfall (and this is true even of datum site occurences) unless its presence is considered in relation not only to the rainfall but in relation also to the nature of the soil surface on which that rain falls, and in relation to the total range of the plant. All soils which absorb their whole rainfall and no other water are datum soils. But within that definition one datum soil may differ greatly from another in terms of growth values to perennials depending on the proportion of the total water receipt which is retained against evaporation loss at the soil surface.

Acacia seyal, as has been recorded above, grows on the very heavy and seasonally inundated clays of the Upper Nile

/swamps and

swamps and also on the gritty valley beds of the Nubian sandstone areas four hundred miles north. In the former case it receives over 1000 mms. of rain. In the latter the rainfall is 100 mms which may flush the valleys three times in a season for an hour at a time.

Taking datum soils it is recorded on clays in 600 mms of rain and on sands in under 250 mms.

Hence as a species A. seyal is typical neither of the clays nor of the grits nor of the sands, nor of any one of the three rainfalls. But there are conditions prevailing in the one site which are reproduced in the other sites and which must be combined to suit the species since it grows there.

The distribution records of Sudan tree species show that their site indicator values follow several rules very consistently. The differences in soil texture and in rainfall throughout the range of a species are seen to be complementary differences.

This consistent behaviour of all species in regard to distribution can best be illustrated by the use of charts representing diagrammatically the different sites, with particular reference to contour as it affects surface water movement. Charts have accordingly been prepared from the records of occurrences and these charts will be called Distribution Transects. It was not until these had been made and compared that the problems of apparently anomalous distribution resolved themselves. These transects take four forms according to the aspect of distribution to be shown.

(ii) The Contour Transect.

First of all it is necessary to show how species vary with contour and with the character of their soil surface in a single observation area, that is to say in a limited piece of territory, say 4-5 square miles in extent lying in one rainfall but having varied surface and contour. The observation area is normally sufficiently extensive to include datum soils as well as soils divergent in the two typical ways from the datum, namely on-flow and off-flow soils.

The chart shows the distribution of various species across these various sites in one rainfall.

This is the Contour Transect and is the record of field ecology in an area of one rainfall. It supplies, to borrow the soil term of Milne, the 'Catena' for the vegetation of that area. Plate XI illustrates the Contour Transect.

(iii) The Rainfall Transect.

When it became obvious that that all species occur in widely differing rainfalls it became necessary to show the

differences

different types of site on which each single species occurs at the various parts of its rainfall span. Since in a given rainfall a species is almost invariably limited to a single type of site this second form of transect resolves itself into a contour section across the rainfalls showing how the type of site occupied by the single species varies with the changes in rainfall from site to site.

Transects of this second type are called Rainfall Transects and each is for a single species. Each cuts across the latitudinal belts of rainfall and shows how the species creeps from one type of site at the 'wet' end of its range through a particular order or succession of differing sites to the site type which it occupies at its 'dry' terminus. Plate XII is the Rainfall Transect for a single species.

(iv) The Site Transect.

The significance of the abovementioned series of site types becomes apparent when it is found that, with no recorded exceptions, all species progress through their rainfall span via the same sequence of site types. This sequence has as its central group the datum soils. Astride this datum, on one side the occurence sites have water receipts in excess of the receipts of the datum sites; on the other side are the sites having receipts less than the receipts of the datum sites.

The graphic representation of this series of site types as confirmed in each rainfall transect for a species, and found to be common to all species, may be called the Site Transect Plate XIII (there is one single Site Transect, whereas there is a rainfall transect for each species).

The site types included in the Site Transect may not all occur in a single Contour Transect, certain site types e.g. ponds, or mountains, or rivers may be absent from that piece of country. To sum up these paragraphs the Contour Transect purports to show how the various species there existing are distributed across the various sites in a single observation area, in one rainfall. The Rainfall Transect shows, for one species, how its site type varies with rainfall. The Site Transect thereafter shows the comparative values, in terms of absolute growth water, of the various site types.

Resuming consideration of the significance of the Site Transect as thus revealed by the Rainfall Transects, and regarding the Site Transect as a section across increasing rainfalls then the Site Transect so far as one species occupies it, is a record of equiconditional sites so far as available moisture is concerned. Sites which so differ from one another as to be equiconditional in widely differing rainfalls cannot be equi-conditional site types when they occur together in a single rainfall. This is

/confirmed by

confirmed by the species distribution in any Contour Transect.

Further conclusions are that, in a given rainfall, the sites of least available water for the growth of perennial plants are sites of those types to which all species recede in the wettest parts of their range, and that those sites in any Contour Transect of an area which have the greatest available water for perennials, and are able to support the highest moisture demanders of all the species sharing the Contour Transect in question, are of those site types which are demonstrated in all the Rainfall Transects to be the dry terminal occurrences of the transect species. In other words, the Contour Transect for a given rainfall shows that each particular species is limited to a certain site type in that one particular rainfall. The Rainfall Transects show that species are by no means limited to a narrow rainfall span and also show the type site each species requires in each rainfall. The Site Transect extracts the various types of site found in the Rainfall Transects and gives them in order of water availability for perennials, an order which is found to be constant in all the Rainfall Transects.

(v) The Belt Transect.

Lastly we have the Belt Transect, a single transect or indeed merely a list showing the order in which species succeed one another on any one and the same type of site in gradually changing rainfalls.

Any one particular type of site may be chosen as the site type on which to trace the change of species with rainfall on such a type of site. But because of the difficultiesin measuring the growth value of run-off water lost, or of on-flow gained, the obvious type of site on which to trace species change is the datum soil. But the same succession is revealed by taking any one of the other site types, such as briefly flooded hollows, or rocky hillsides, and tracing the vegetation occurring on that one site type from the 1400 mms isohyet to the 50 mms isohyet, through, that is to say, a succession of rainfall stations.

What is so often and so uselessly attempted, is to demand resemblances in soil or in rainfall (one or other being taken separately) between a hill-side site carrying a particular species, and, say, a plain of cracking clay soil carrying the same species. The two sites, on the evidence of the species common to both, are equi-conditional sites. But they only are equi-conditional sites because they are different from one another in soil and complementarily different in their water equation.

When the isohyets are crossed from 1400 mms of rain to 50 mms of rain travelling on datum soils all the way, assuming such an undisturbed line of datum soils can be found (the longest is in fact the Sobat-Roseires-Atbara-Line) species are

/found in

found in their decreasing moisture sequence. Similarly along a series of hill sites from the wet end of this thousand mile country to the dry, the same species series is repeated, in the same order. But on the hill sites the series stretches over a span of lower rainfalls than the same series does in the journey over datum soils, with new species from wetter items represented on the hills at the wet terminus which are not found on the other sites traversed, in that rainfall. Similarly on a journey across sites liable to inundation the series stretches over a span of heavier rainfalls than the same series on the datum sites or on the hill sites.

The hills studied for this purpose are hills so low as to be without altitude effect on rainfall being only 50' to 100' above the plains. The change is a matter of soil surface and its effect on the utilisation of the same amount of rain as falls on the adjoining datum soils. No such line of hills exists as a continuous range in the Sudan and no completely continuous line of datum soils exists over the thousand mile line representing this rainfall span in the Sudan. But an adequate series of inselbergs and monadnocks is available, suitably spaced, and an adequate if also discontinuous series of datum soils separates them and on these two series the moisture sequence was worked out, to reveal the belt transect.

The belt transect is simply the list of type species in their order of moisture demand derived from their occurrence in the several site series each a series of comparable site types, crossing the isohyets. Contour and rainfall transects have been prepared from the data collected in every province of the Sudan. Belt transects have been prepared from the occurrences recorded by the writer. The evidence of these confirms the moisture sequence revealed by comparison one with another of the whole series of rainfall and contour transects and provides confirmation of the evaluation of sites which is made in the site transect.

(vi) Examples of Transects. See Plates XI et seq.

(vii) Analysis of Transects.

Analysis of transects reveals :-

(a) That the occurrence sites of any given species, beginning at that end of its range which occurs in heaviest rainfall and ending where the species disappears at the dry end of its range, succeed one another in the following order :-

Loams. A. Hard soil slopes i.e. sheet slopes, not readily capable of absorbing water and usually subject to some sheet erosion. These are studied in detail in Part III Chapter I.

/D. High

B. High lying old flood plains, subject now to inundation for days at a time, usually from river water, but also occasionally from rain water.

C. Low flood plains inundated for weeks at a time.

Clays

D. Mounds in swamp, and high banks fringing rivers which traverse swamp.

E. The beds of land-locked pools known as 'rahads' in rainland, and as 'mayaas' or basins where they fill from rivers, holding water for months.

F. Clay plains known as badobe soil. These rarely give rise to run-off and water seldom stands on them.

G. Mature sand plains on which dunes have now been flattened out.

Sands

H. Immature sand, including raw or partly-fixed dunes known as 'qoz'.

I. Pockets or small hollows in sand country receiving extra water but maintaining good percolation. Also valley beds of open readily permeable sandy ~~beds~~ soils.

K. Hills of rough/rocky highly absorptive surface.

L. Large seasonal water-courses flushing after rains.

M. Hard plains of grit or rock.

N. Small runnels flushing for an hour or two during rain.

O. Perennial streams or rivers.

These site types are shown in Plate XIII in the order which has been found to be that in which a species uses them in decreasing rainfall from left to right.

(b) That the sites on which a species can survive on least rainfall are coarse sands hill-sides and gritty runnels, and that the sites in heaviest rainfall are inundated sites and non-absorbent soils on hard-surfaced slopes.

/(c) That

(c) That species occur in a definite succession on the same one type of site (where such type is represented) from the wet end of the country to the dry end. Many notable absences are recorded in particular districts, where the rainfalls, considered alone, would suit them. The most marked instances of this are noted where no sands exist in clay plain country or where no heavy clays exist in a wide area of sands.

(d) That the species preserve this order of occurrence if examined on any <u>one</u> type of site across the several rainfalls.

(e) That in any <u>one</u> rainfall locality these different types of site have different water values.

(f) That types of site can be arranged, for any rainfall in order of water value, and that this order is the same as that in which the sites carrying a given species occur in the rainfall transect for that species.

(g) That a species has no indicator value for soil or for rainfall until its rainfall transect has been determined, but that thereafter use of its occurrence site type makes it an accurate indicator of rainfall, and, on datum soils, the rainfall, if known, makes the species a precise indicator of clay content.

Reference is made in Part <u>III</u> Chapter <u>IV</u> to the practical uses of these facts. It is here only necessary to point to a corollary of the above, namely that where a datum soil has to be chosen on which to establish an absent species in a known rainfall, the problem resolves itself into a search for a soil of a clay content appropriate to the needs of the species in this particular rainfall.

PART II - CHAPTER IV - VERSATILITY OF SPECIES COMPARED WITH EQUI-CONDITION OF SITES, AS ALTERNATIVE EXPLANATIONS OF ANOMALOUS DISTRIBUTION.

These apparently anomalous occurrences, examples of the very many noted in the occurrence records, raise two questions :-

a. are such tree species highly versatile in terms of the soil texture and water factors, or
b. are apparently divergent sites in fact not divergent but equi-conditional in terms of a dual or combined soil-water factor?

(i) Tolerance in regard to the Soil Texture Factor.

Few measurements of the versatility of tree species have been made in terms of any habitat factor, other than, under laboratory conditions, on wilting point and chemical nutritional factors.

Opportunities for the study of factor-range of tree species in their natural distribution have long since disappeared in most civilized or heavily populated countries. Apart from fragments of Cupuliferous scrub and some Pinus sylvestris of doubtful history there remains very little living and undisputable evidence of natural range in Britain. But in the African continent are many areas where even populated Sudan is such an area.

the influence of man has been unchanging for centuries. The lightly

The introducer of plants is one of the first to study versatility in practical field terms. When the introducer usually starts without freedom of choice as to site, and, labels his introductions successes or failures, overlooking the obverse which is that the site has probably failed the plant, and often omitting a search for the cause.

Versatility is certainly less often studied in indigenous species than in exotics introduced or proposed for introduction. Consequently exotics come to be introduced without precise knowledge of the range or factor span which they occupy in the country of their origin, and thus without precise knowledge of the comparable values of the new sites to be offered to them.

In the sub-tropical conditions of the Sudan, as has been noted, it is inevitable, in any evaluation of a site, that concentration should first be on the moisture factor.

The study of the moisture factor inexorably becomes a study of soil texture, and range in relation to moisture has

/been found

been found interpretable only in terms of range in relation to physical conditions, to the exclusion of the temperature factor. The chemical factor also must be included over any wide range though it may achieve importance independently of the moisture relation in strictly local differentiation of soils. It may also, as in the presence, or the use, of lime and gypsum, have vital significance in terms of the moisture relation.

Are some species more versatile than others in terms of habitat factors? If so are they versatile in response to all locality factors, or in one factor only, or in terms of pairs or of groups of factors. Is versatility in one factor dependent on constancy in other factors, or is it inter-dependent on changes in them? Are certain changes complementary?

This chapter deals with versatility in terms of clay-content, with versatility in terms of water requirement as shown by water receipt, and with versatility, or the lack of it, in terms of the combined clay / water factor.

First of all it must be recognized that most species can be established artificially out-with the range in which they can establish themselves by natural regeneration even when seed is present. For instance the device of mound planting has been evolved for areas which are liable to shallow surface flooding after the sowing date. This is a common device in the agricultural practise of the nilotic Shilluk, Nuer and Dinka tribes who commonly sow seed at three levels on their mounds in the hope of covering all combinations of flood and rainfall. Again, sakellarides cotton, which requires over 1200 mms of applied irrigation water on clays, has been grown by the writer on sands receiving only 100 mms on rainfall, by the use of seedling plants raised in pots to a stage at which they were no longer vulnerable to attrition by moving sand grains. Transplanted ~~plants~~ on sand, plants of this cotton have survived seven rainless months and continued growth into a second rainy season. From the successes attained by planting out with the natural occurence zones it is concluded that there is, for each species, an existence versatility and a natural reproduction versatility or repetition versatility, and that the former covers a wider range of factor space than the latter. It has been proved on fire-protected areas, that many habitats are suitable in soil and water conditions to a vastly greater number of species than occur on them, but are unsuited by annual grass fires, to all but fire-resisting species. Few species occur in nature both on fire-favourable and on adjoining fire-unfavourable sites, but this does not prove that either site is outside their soil-rainfall range.

Two of the great Acacia belts owe their purity to their superior fire-resisting powers.

/Acacia seyal

Acacia seyal resists the hottest fires by its flaky bark.

Acacia mellifera suppresses in its shade the grasses which its soils and its rainfalls are suited to growing. Erythrina tomentosa, Cussonia arborea, Diospyros mespiliformis and Balanites aegyptiaca resist fire by extreme formation of corky bark.

There are examples of species which are restricted, within the soil-moisture span appropriate to their needs, by a third and man-made factor, fire, but which resist that factor more successfully than many species which for fire reasons are absent from parts of their appropriate soil-moisture span.

Coming now to consider the precise values to be attached to factor span, in texture of soil or of rainfall, taken separately, there is evidence that species can thrive on soils which cover a very wide texture range.

Taking natural occurences only, though as has been noted above this is likely to be a narrower span than could be utilizable with artificial methods, the sites sampled for seven type tree species showed the following ranges of clay content as being capable of producing successful growth of the species against which they are shown :-

Acacia seyal:	3%	to	78%	clay content.
Acacia mellifera:	20%	to	59%	" "
Dalbergia melanoxylon:	2%	to	57%	" "
Tamarindus indica:	26%	to	57%	" "
Prosopis africana:	3%	to	37%	" "
Terminalia brownei:	4%	to	43%	" "
Combretum ghasalense:	2%	to	16%	" "

These determinations by themselves show an unexpectedly wide versatility in terms of soil texture. In fact, with the possible exception of the last species, which the writer has not yet found on heavy clays, they dispose of any suggestion that any one of these species was a species 'typical of clay soils', or 'typical of sands', or 'a species which requires a fresh loam'.

Wide as is the range of tolerance they show, it is not to be supposed that the sites recorded necessarily include the limits, in either direction, of the texture range of any one of these species. The above figures are from natural occurences. Certain experiences in the artificial establishment of two Sudan tree species are of significance at this stage. They are Khaya senegalensis, Juss. Acacia arabica, Willd.

Khaya senegalensis Juss. the Sudan Mahogany, was taken from one of its natural occurence areas in Equatoria Province, on a 57% clay in 1050 millimetres of rainfall, and was successfully established experimentally on a 12% clay and on a 65% clay, both in dry country five hundred miles outside the natural occurence limits of the species. On the 12% clay this species

/succeeded on

succeeded on 420 millimetres of rainfall. On the 65% clay it succeeded on 300 millimetres of rain with, in addition, over 1200 millimetres of applied irrigation water per annum.

At the time these trials were made they were no more than hopeful experiments, since it was not until four years later that this species was found to occur naturally on 45% clays in dry parts (300 mms of rain) of remote Darfur.

Acacia arabica, is a species thriving indigenously on inundated river lands of the Nile from Egypt southwards to Abu Zeid ford near Kosti on the White Nile, and to a point near Roseires on the Blue Nile. It does not occur in nature south of these points. But by repeated efforts, justified by the high value of the species, a technique has been evolved whereby it can be established by sowings at points as far south as Juba, over five hundred miles south of the abrupt natural terminus of the species at Abu Zeid ford.

Data on the clay contents of these artificial plantations south of the ford (Shukaba, Zarzour, and Tewfikia) are available for comparison with clay data for Acacia arabica soils within its natural range. It is to be noted that the water regime of all those sites is not determined being a combination of flood and rain. The subject under discussion on these sites is versatility in terms of clay content not of chresard.

The clay content of sites of good growth and of poor growth were determined in all the cases quoted.

In Plate XVIII the sites favouring growth are shown in one vertical sequence and the unfavourable sites in another. Sites in the natural zone of the species are shown in blue and sites established artificially outside that zone are shown in red. The average clay contents of good sites and bad sites in each of these two zones have been connected by a line in the diagram.

At Zarzour, in the 62%-78% clay range, the difference in clay content between good sites and bad is 17%.

At Shukaba, where the plantation is under rainfall only, in the 55%-65% clay range, this difference is 3% only.

At Gebel Bowser, an inundated forest in the 25% - 47% clay range the difference between the averages is again 3%.

It appears from these values that unit difference in clay content is less significant at the higher clay contents than at the lower clay contents. Further study of the Mitscherlich-Lundegardh law of relatively in its application to the clay factor is called for.

/Lundegradh (1931)

Lundegårdh (1931) has given the law in the following words:-

> " The more nearly a factor is in minimum in relation to the other factors acting upon the organism the greater is the relative influence of a change of that factor upon the growth of the organism. As a factor increases in intensity its relative effect upon the organism decreases; and when the factor is in the region of its maximum the effect of a change, upon the organism is nil".

Examining the data for the sites of natural occurence and comparing them with those for introduction sites outside the Acacia arabica natural occurence zone, the two definite ranges can be distinguished water opportunity being assumed adequate in each range, since the species grows in both, though not necessarily equal.

First, the zone denoting the range of versatility where natural regeneration is involved. This extends from 25% to 46% of clay content.

Second, a zone denoting the range of versatility where natural or artificial regeneration is involved. This extends from 25% to 78% clay content. That is to say, the natural regeneration span of 21% is increased to an artificial regeneration span of 53% clay content variation.

A further extention into soils of lower clay content than any of the above has more recently succeeded.

In the bed of the Gash, an inland river rising in the mountains of the former Italian territory of Eritrea and terminating in an inland delta in Kassala Province, Anglo-Egyptian Sudan, Acacia arabica has been sown as a soil fixer on irrigation control spurs artificially initiated by masonry. On silt deposits lying a little back from the main channel and having a clay content of 25% to 30% Acacia arabica succeeded from seed sown direct as the flood receded. But in the almost pure sands in the bed of the main channel and alongside it, percolation loss downwards was so rapid after the final flush and flow of the season that the seedling roots were unable to follow the falling level of available soil water fast enough to maintain contact with it and were [illegible] off in a few weeks. To overcome this, seedlings were raised in open-bottomed tin pots 10" long by 2" diameter and the complete plant and pot were planted in the difficult channels. The roots of the pre-raised seedling thus planted have been able to keep touch with the falling water level and a highly porous sand becomes into the range for Acacia arabica if given this treatment.

Further evidence of tolerance of a wide texture range is afforded by the distribution of Acacia tortilis one of the Acacias which penetrates furthest towards desert conditions.

/The soil

The soil texture tolerance of this species is illustrated by the data given below which was collected by the writer in Northern and Western Kordofan.

Wady el Ku, Northern Kordofan.

A site on sandy slopes above the flood level of the valley, the slopes carrying Acacia tortilis. Some parts of the slopes adjacent to the sample pit showed wash (i.e. run-off) effects. The rainfall is 125 mms. The clay content is 4.7%.

Wady Mogarr, Northern Kordofan.

A site on the Nubian sandstone slopes leading to the valley, a quaternary river bed, but not themselves inundated. The rainfall from the isohyets is 140 mms. The clay content is 6%.

A second site, immediately adjoining the above was a rain-formed surface pan eighteen inches lower than the preceding site and subject to brief and localised rain flooding. This pan carried dead young Acacia tortilis.

The site is in the 140 mms. isohyet but was trapping from run-off more than its own precipitation receipt.. The clay content is 16.2%.

Jebel Um Shedeira, Northern Kordofan.

In the shallow valley near this hill and at its western base, on the road from Soderi to El Obeid the surface is subject to light flooding after rains. The site is in the 270 mms. isohyet and Acacia tortilis is thriving. The clay content is 13.4%.

Wady el Ku, Northern Kordofan.

This site is in the same area as the first in this case the sample pit was in the valley bed itself, on which water stands for some weeks after rains. The site carried well-grown old Acacia tortilis thus exhibiting the flood tolerance of this species, a fact also noticeable on a wider scale in the flooded basins on the lower course of the River Atbara. The rainfall isohyet is 125 mms. The clay content is 68.8%.

Closely adjoining this site, within twenty yards of it Acacia arabica, a species highly tolerant of flooding, was dead on a clay content of 61.8% and alive and healthy on a clay content of 44.4%.

From this range of samples it is to be noted that Acacia tortilis occurs on soils of clay contents ranging from 4.7% to 68%. It is also to be noted that the species occurs on both inundated soils and on soils receiving rainfall only.

/It is

this increase, slight as it is, is a sufficient change to displace one species in favour of another. Thus between [illegible] el [illegible] and [illegible] on a uniform type of Gatum soil, Acacia mellifera, Acacia fistula, Acacia senegal, and Acacia seyal, subdivide, in that order, a rainfall span of only 200 mms. namely the span between the 400 mms. and the 600 mms. isohyets. Each of these species appropriates a precise rainfall belt within this 200 mms. span, to the virtual exclusion, on that soil type, of the other three species. The four species reveal here, the same moisture requirement sequence which they exhibit throughout their whole distribution in the Sudan.

The conclusion is that on a uniform Gatum soil in balance with its rainfall to the extent of being able to absorb all the rainfall it receives, and receiving no other moisture, versatility in the rainfall factor of the species is not in evidence.

Considering transects across Gatum and non-Gatum soils also, the distribution of species exhibits no versatility in any one contour transect. There is in each transect one particular type of site in that transect in which the species finds its moisture need. A significant example of apparent versatility has been pointed out by Greene (36) for irrigated conditions where applied water has been measured.

"The amount of water required to mature a crop of cotton varies greatly with locality. In the Punjab it has been estimated (Wilson) at 6000 m3 per hectare; in Egypt the figure is about 10,000 m3 per hectare (Dudgeon; Molesworth and Yenidunia), in the Sudan Gezira about 15000 m3 per hectare are required".

These differences, together with the results of [illegible] cotton on a sand dune, may appear to betoken versatility in the plant but only in terms of the amounts of water applied to the soil or falling on it as rain, and it would be wrong to assume, on these facts, a versatility in terms of water available to, or absorbed by, the plant.

It is suggested that if clay contents typical of the soils in these four sites be compared, for the same type of cotton, it will be found that the vast differences in the amounts of water required to be applied ~~xxx~~ bear a complementary relation to the texture of the soils as measured by their clay contents.

Assuming that, in the comparison made by Greene, to which the writer would add his rainfall result quoted, the data apply to the same type of cotton in each case (as is the case in the two Sudan examples) assumed values for the clay contents of the Punjab and Egyptian sites compared with the known values for the two Sudan sites are shown by the intersections of the vertical abscissae in the diagram given on Plate XIX.

/The degree

The degree of accuracy within which the texture of the Punjaub soils and the Egyptian soils are thus deduced is of less moment than the conclusion to which the Sudan experiments lead namely that the heavier the soil texture, the greater the amount of water, applied at the surface in rain or by irrigation, required to mature a given plant.

Equicondition.

The conclusion is thus reached that a species is versatile in terms of either the soil-texture factor or the rainfall factor if these are considered as separate unrelated factors, but that it is not versatile in terms of the dual texture-rainfall factor.

The subject is further discussed, for datum soil occurences, in Part III Chapter I hereafter.

The records of anomalous distribution, and the study of the case for versatility in each of two factors studied separately are now to be examined in the light of the theory which regards the moisture demand of the species, measured as rain or as water added, as conditioned by the texture of the surface soil of its site, and the soil texture requirement of a species as being conditioned by water receipt of the site.

In the light of this theory, there is for a given water condition, a very limited range of texture on which a given species will thrive, and for a given soil texture there is a very limited water range which is, for that texture of soil, the inexorable water demand of the species.

PART III - CHAPTER I. SOIL DEVELOPMENT AND MOVEMENT.

A. INTRODUCTORY.

If the preceding chapters have led to the impression that there are fourteen site types in the Sudan each unvarying in itself and each defined by hard and fast criteria, this impression must now be corrected. This can conveniently be done by taking two of these site types and analysing these. The site types chosen are datum sites and sheet slope sites. It has been shown that there are two very distinct types of datum, namely datum clay soils and datum sand soils. Between the extremes of datum sands with a clay content of only 2% and the recorded extremes of datum clays with a clay content of up to 35%, there is a wide range of intermediate types still truly datum soils losing no water by run-off and receiving nothing in excess of their rainfall.

In another site type, namely the run-off slopes commonly found at hill bases, there is a wide range of sites all classifiable as run-off or sheet slopes but varying from one another in angle of slope, in amount of water movement over their surface, and in the degree to which they have retained their soil against moving water and gravity.

B. A STUDY OF DATUM SOIL SITES.

Note : The following terms, adopted by Clements, have been found precise and convenient for the purposes of the present work and have been used with the meanings shown :-

Chresard - The water in the soil available to plant growth.

Echard - The water held by the soil and not available to plant growth.

Holard - The sum of the chresard and the echard.

(i) Soils and their rainfall.

Various methods of summarizing mechanical analyses in respect of particle size are in use, notably, in African work, the "texture" ratio used by Doyne and Watson in their Nigerian soil work (45 p. 105) and the capillary rise measurement used by Sudan soil chemists.

These methods are of great value for the laboratory comparison of laboratory results and will probably also be found significant in interpretation of distribution. The

/writer finds

writer finds the simple clay content to be of greater use in the field comparison of soils in terms of plant growth on them.

In a search for conditions of true and long-termed stability of soil, either in the surface profile (see G. Milne in "Nature" Vol.135 page 548 on use of the term 'profile') or in their nature, the enquirer is led to the clay plains. The purity of species over vast areas of land even with increase of rainfall is a feature of mature plains. This can only be taken to imply a relative constancy in the climax sward over these wide areas, even though they stretch across the isohyets. In these plains, and in these plains only, has the soil-water regime reached an unchanging constant over wide areas. The mature clay plains are in a balance of such a nature with their rainfall that all precipitations of rainfall are absorbed by the soil and held by it against gravity. Except in extreme conditions (for instance, 'Cloud burst') there is no surface water movement over them, and no gravitational loss downwards through them - the lowest layers are dry. Vageler (75 p. 1[illegible]) describes sheet movement and gives an absorption maximum. Sheet movement does not occur on the mature 'badobe' or clay plains of the Sudan. Animal traffic on wet clays immediately upsets the precipitation-absorption balance and results in standing surface water. Furthermore, the soils such as those of shallow depressions adjoining rivers, where, for reasons of river rise or for catchment reasons, water is impounded annually or periodically, lose their ability to absorb their rainfall even in years of no impounding, and become subject to slow surface movement of unabsorbed water arising from their own rainfall, and irrespective of impounding, or of catchment from adjoining areas.

In the wide mature clay plains above the river pounding-line there is no run-off from water falling on the clays. In such areas a water-course is invariably traceable to an elevated distant area, where soil character checks absorption, or where mere contour has caused a run-off from an otherwise absorptive soil. A similar delicate balance between soil surface absorption and rainfall can occasionally be traced on other types of soil. A flat red sand, for instance, may be capable of absorbing steadily the heaviest down-pour so long as the rain reaches it in the even natural distribution of rainfall, whereas the run-off from a motor car, or similar obstruction, standing on it causes a series of minute streams to run off unabsorbed by the soil surface. Animal pounding is a certain cause of increased run-off. Animal tracks notoriously develop into water courses. The town of Nahud is the source of several rainy season rivers on a sandy soil perfectly capable, where unisturbed, of absorbing all its rainfall. Cultivation of the flat sands, on the other hand, increases absorption. There is a local belief in eastern Kordofan that temporary rain season wells are caused, by cultivation, to yield water in sites which would otherwise be dry at that depth. It is not

/the ability

the ability to admit the annual rainfall to pass into the soil which constitutes a soil in balance with its rainfall, but the ability to admit it, to absorb it, and to hold it at the upper levels as against gravity, but not against evaporation, which characterizes the climatic datum soil. Sands which can do these things are sands of a particle size so small as to cause them to behave as clays. (Ramann in 5 p. 208).

Laterites which could do this would be soils affording such resistance to downward percolation of water that they would cease to be subject to the leaching which has given them, and maintains for them, their principle characteristics. (58). It is such a metamorphosis from a leached to an unleached type which overtakes the detritus of lateritic slopes so soon as it reaches a valley bottom subject to annual flooding from the red lateritic slopes. In these new surroundings it rapidly becomes, instead of a red grit, a black-cracked clay, resilicated to a condition in which it holds water against gravity and also against the suction of plant roots, but not against evaporation.

(ii) Clay content in relation to rainfall.

The nature of this relationship between a plains clay and its rainfall must now be considered.

On the northern frontier heavy seasonally cracking clays do not exist out-with the present or most recent flood plains of the Nile. In the 5" isohyet cracking clay soils do not occur on sites whose soil is subject to the action of direct rainfall only. There is however evidence of soils which at some date in the distant past received a rainfall sufficiently heavy to cause them to crack.

Proceeding south, cracking of clays, under rainfall only, first becomes noticeable in the northern part of the *Acacia mellifera* belt, in rainfalls of about 250 mms. as in the northern Butana. Commonly it is first seen where run-off has been held up by artificial banks called terraces on Butana plains. From that line southwards throughout the whole range of the clays, cracking, under rainfall only, occurs on clays, in a degree which increases southwards.

The cracking becomes increasingly noticeable with increasing rainfall. Exceptions occur over still unweathered outcrops of low clay content, where erosion has proceeded far enough to remove all surface irregularity. Percolation downwards is maintained by the nature of the surface soil and of underlying absorptive strata (as is known from experience in well sinking) to such a degree that the surface covering has not grown in clay content to the datum content for the existing rainfall. Such patches in eastern clay plains, not hill bases, are called 'Azaza'.

/In the

In the 100 mm. rainfall line in the sandy country of northern Kordofan clay is found in the hollows between geologically young dunes.

But comparatively heavy uncracked clays exist in the drier zones of 50-100 mms. of present rainfall, while such a rainfall is unable to change even the worst drained hollows in recent sand to a higher clay content. This would point to certain rainfall clays in the driest zones being the result of heavier rainfalls than now fall on the material out of which they must have been formed. Subjected now to rainfalls less than the rainfall which formed them, they either have lost the character of cracking or fail to receive sufficient water of imbibition fully to swell their clay content under rainfall, i.e. to get their chresard value.

The extreme uniformity in soil nature for a given rainfall wherever extensive mature plains exist, betokens a clay-rainfall equation and this is confirmed by such soil surveys as that of the Gezira plain. The following clay contents, on the latitudes shown, are from Dunn (20) :-

on latitude	14°	25'	..	average 49%
on latitude	14°	35'	..	average 52.8%
on latitude	14°	45'	..	average 47.6%
on latitude	15°	55'	..	average 45.2%
on latitude	15°	05'	..	average 44.3%.

The uniformity of vegetation of many plains across the isohyets betokens a relative constancy in the chresard despite increasing rainfall. It is concluded that the phenomenon of increase in clay content which accompanies increase of surface receipt, is the reason why chresard is not proportional to surface receipt, but that in clay plains the chesard increases at a much lower rate than is represented by the rainfall increase. (See the remark by Trevor already quoted).

Confirmatory evidence of the fact that increased water receipt coincides with increased clay content can be found in any one zone by a study, within any single zone, of sites receiving water in excess of the rainfall of the site, as by damming back, or flooding from localised catchment areas from which there is a run-off. Conjointly a study of sites having less moisture as holard than the rainfall of the zone provides, e.g. areas of run-off, and areas of high water loss from vertical percolation, completes the picture. This subject is dealt with under the headings "Clay content in relation to contour" and "The nature of pre-datum and post-datum soils"..

(iii) Clay content

(iii) Clay content in relation to contour.

Emphasis has been laid on the fact that the datum clay content is to be found, typically, on clay plains mature in profile, approaching the perfect plain and in receipt of rainfall water only.

The closeness of approach to the perfect plain achieved by nature can be measured from the contour maps of the Gezira plain between the two Niles, and of other areas.

The average surface slope of the Gezira plain is .17 metres per kilometre. The average slope of the clay plains of the Gedaref-Gallabat-Lafuza triangle, in Kassala Province, is 1.5 metres per kilometre. The few and typically discontinuous water courses which traverse these latter serve to carry, not rainfall unabsorbed by the clays, but the run-off from distant steep rocky catchments on inselbergs or groups of inselbergs.

The formation of heavy clays is not confined to soils of these slopes. It can occur on gently undulating slopes and even on slopes so steep as that of Hillet el Onis near Doka on the Gedaref-Gallabat road. The reasons why the clay blanket does <u>not</u> clothe certain hill slopes may be summarized as :-

A. High vertical loss from the superior percolation afforded by exposed strata on hill sides, or by recent detritus eroded therefrom. Percolation loss is associated with reduction of the clay potential of the site.

The nature of some of the heavy clays is proved by sections exposed in the Kerrib (eroded slopes) on the Hillet Hakuma-Sofi road along the Atbara Kerrib. In these cases a clay blanket several feet deep has formed on gently sloping land out of basalts despite good downward drainage opportunities.

B. Heavy run-off, causing, besides removal of clay in formation, a reduction of the mean climatic hola rd.

Run-off reaches the highest proportion of total precipitations on uncracked low content clays such as from the soils known as 'Gardood' which fringe the Kordofan sands and form a soil condition of uncracked surface. These hardened loams commonly occur on all hill plinths and form the sites classified as sheet slopes.

'Hafirs' (ponds to store rain water) if required to hold water in the early rains must be close to such plinths and situated in comparatively low clay-content soils (e.g. in pre-datum soils).

Grasses sprout on the sands long before the early rains have restored the colour of adjoining clays and given a surplus as sward which can initiate grass growth. It takes prolonged and heavy early rainfall to saturate heavy clays and close the dry season cracks.

Loams, ('Gardood' soils) on the other hand, are subjected to a surface hardening by the first rains this tends to form a skin inimical to absorption of subsequent showers. Further, even the lightest sands of the goz (dune) soils of eastern Kordofan tend to develop a skin wherever water moves over their surface. It is not the presence of water on their surface which appears significant in forming skin but the flow, however slow, of water over them.

The not-level surface afforded by rocks at once sets up flows which remove clay-forming materials. Where no rocky projections or impermeable plinths occur, progress to higher clay content occurs, even on slopes.

In this section on contour so far only areas surviving at a level above that of the surrounding plain have been considered.

Coming now to consider depressions including any plains area which, for any reason, receives on its surface more water than falls on it in the form of rain or other atmospheric precipitation, an area the water receipt of which exceeds its precipitation-receipt.

Such plains areas (naturally here the beds of deep water-channels such as rivers, streams and Khors, that is to say seasonal streams, are excluded without excluding wide shallow and flats over which the rivers spread in flood) invariably have a higher clay content than surrounding soils receiving rainfall only. Whether this is in some cases solely the result of deposit from the waters moving slowly on to them is open to further study. But the conditions in the red-ironstone area indicate that increased moisture is the prime factor irrespective of particle size, since in those areas the large, gritty, fast-borne and first deposited red detritus is itself speedily transformed to fine-particled black clays in the inundated valleys, while the River Jur sixty miles beyond the laterite country is still red with suspended particles in its flood season. Further, in the Upper Nile flood plains where far-carried material of common alluvial origin is subject to varying degrees of annual inundation, clay content varies locally with degree of flooding, much more closely than with distance from the source of the suspended materials.

Sections across the contours at Zarzur and at Tewfikia (Plate XX) serve to illustrate clay variation with degree of flooding. These sites are 300-400 miles from the nearest eroding slopes whose drainage reaches the river. A section down to the lower flood plain of the Jur at Nyin Akok (

/shows

shows a similar relation. In this case the clay plain is close to the eroding source of part of the material out of which clay has been formed on the flood plain. At Tawfikia the whole section is below former flood levels.

The growth of basin clays from original sand and silt, or from low clay content soils, under repeated subsequent floodings, the changes in inundated sand banks after their fixation as islands (e.g. Gereif island between 1929 and 1938) the drop in clay which accompanies artificial elevation of a soil to form a bank, and above all the increase in clay content which is found to follow water pounding by artificial banks locally called 'terraces' (a case in which run-off is prevented rather than outside water collected) all stand in support of the active importance of increased water by itself, irrespective of anything it may carry and deposit, as a factor increasing the proportion of fine particles in the soils of depressions.

(iv) The Climax or Datum Clay Content.

To summarise, it is found that clay content bears a relation to the amount of water reaching the soil surface, that this relation approaches a constant for a given rainfall where the soil absorbs and holds against gravity the total precipitation on it but receives no other water.

At a given rainfall, only soils having as their clay content the content appropriate to their rainfall are capable of doing this, against gravitational loss (surface or vertical). Excess of clay content tends to surface loss, an extreme deficit of clay tends to percolation loss.

It is found that sites on slopes which lose part of their own precipitations through gravitational loss (surface flow) have clay contents below the climatic datum content, or normal, and that sites which normally receive surface water in addition to precipitation-receipt have clay contents in excess of the climatic datum clay content.

Since, theoretically, a perfect balance would only be possible in equal annual rainfall equally distributed, since rainfalls are in fact variable, it follows that a soil represents a mean of conditions which vary within more or less narrow but nevertheless significant limits, a series of dry years rendering a clay more capable of yielding to the plant root the normal rainfall of subsequent years, and a series of heavy rainfall years rendering vegetation less capable of thriving on normal precipitation in their course.

The regular and striking changes in the composition of the herbaceous annual vegetation on the clay plains are partly attributable to this cause, as also certain of the grass-less areas due to seed failure, areas called 'mahal' by the Arabs.

(vi) The nature

(v) <u>The nature of pre-datum and post datum soils.</u>

In the conception of soil succession which accepts the climatic datum soil as defined above, directional soil succession <u>on the soils of mature plains</u> has a limited range, these soils being nearly all at or near their terminus of development for the existing climate.

The pre-datum soils sometimes found on the flat in otherwise mature plains are the result of retarded clay formation due to gravitational loss, such as occurs over outcrops of sandstones forming the red patches known as 'Azaza'.

In the typical absence of marked slope, permeability is the potent form of gravitational loss in the few places where it occurs on mature plains. Dry cycles, by reducing the average holard, are a second cause of retarded clay development.

All extremities in surface profile tend to delay maturity, but these extremities are typically absent from the mature plain. In such plains the main delays in the approach to the climax clay content occur in the flat 'azaza' areas of limited extent and are due to their permeability.

So far the soils discussed have been naked, or seasonally surface naked, soils as are practically all the soils of the Sudan plains. On them, while tree growth of various densities is scattered over them, the ground cover of grasses and herbs is normally burned over annually. This is one reason for the excessive surface loss by evaporation from the soil, but certain soils escape fire and maintain a vegetative cover unburned.

An influence retarding clay maturity is certainly plant growth. It acts by increasing permeability and by decreasing the holard by the amount of the chresard transpired. As against this a plant cover protects the soil from surface loss by drying winds. It prolongs the period in which there is a chresard available to itself, and particularly when the annual vegetation dies off and ceases to draw on the chresard, it has a net conservative action on the holard. It reduces the gap between the seasonal extreme of wetness and dryness. It is on sites where this gap is widest that the heaviest clays are found.

Among the factors, then, which delay clay maturity in plains we have :-

1. Gravitational loss chiefly due to permeability.
2. Dry cycles.
3. Plant growth of a type encouraging permeability and reducing surface evaporation.

The chief factor accelerating clay maturity is certainly fire; puddling by rains is second.

/Post datum

Post-climax soils on the mature plains are formed by excess of water, e.g. on flood plains and areas receiving local run-off. If existing under rainfall only, they indicate a previous wetter period, climatic or geographical. They are indicated by a clay content in excess of the climatic mature content. <u>Such post-climax soils constitute habitats particularly low in available perennial water.</u> Any soil the clay content of which is in excess of the climax content has, under rainfall only, a chresard lower than the climatic chresard, and *consequently is, for that rainfall, a relatively dry plant habitat. The extent to which seasonal surface flooding can compensate, on a post-climax soil (i.e. on high clay content) for the low supply of available rain water held as chresard will be referred to later in a comparison of site values with rainfall.

Conversely, soils of clay content below the climax yield more available water from a given rainfall than is obtainable by plants on the climatic mature soil. A permeable soil loses gravitational water (and hence clay maturity is delayed) and at the same time is richer in @available water than the mature clay. This would indicate that, whereas permeability is one form of the gravitational factor delaying clay formation, it is also an index of the factor controlling surface evaporation loss, namely particle size, and that more water is saved by reduced capillary rise to the drying surface than is lost by percolation. There is proof of the higher chresard in permeable soils to be found in every site comparison of species common to sands and clays.

A consideration of the conditions which follow a fall in average rainfall of an area brings out a point of great significance in the study of tropical drought.

Under an original rainfall of <u>x</u> the climax clay content is <u>a</u>. There follows a fall in <u>x</u> to <u>y</u> inches of rainfall. A long period of years (probably at the lower rainfalls and in mature plains conditions a geological period) is necessary for adjustment in clay content to the new rainfall level. In other words the post-climax soil only slowly regains balance with rainfall.

During the whole of that period of adjustment the post climax soils present conditions of extreme thirst to plant growth. The change appears to be proportionately much greater than is indicated by the fall in rainfall. It is probable that there is here an explanation for the suddenness of vegetational retreat before desert conditions induced by a decreasing rainfall. The harsest deserts are usually clay deserts (19). A fall in echard lags far behind the fall in rainfall, and surface losses remain the same under the reduced rainfall (or may even increase due to higher evaporative power of drier conditions) and the whole rainfall decrease is at the expense of the chresard.

* consequently
@ available

/It follows

It follows that species which can exist under a rainfall x on the climatic clay content of x cannot be expected to survive, and do not survive even with a rainfall of x, on soils of a clay content markedly higher than the climax value for x.

Thus far in this section pre-mature and post-mature soil conditions have been considered in plains approaching maturity.

It is obvious that under any given rainfall much more extreme deviations from the climax condition will exist than occur in mature plains, which are the termini in any tropical soil development.

Elevated areas, such as rocky hills, and disturbed areas such as recently carried sand (wind or water borne), and areas of erosion, their detrital plinths and penultimate deposits, are all divergent in greater or less degree from their ultimate fate, namely the mature plain, and it is on such pre-climax sites as these that long range directional soil succession can be studied. Such sites are described in detail in Section G of this Chapter.

Perhaps the most noticeable contrast is between the inselbergs and the clay plains surrounding them. The different conditions offered to plants by these two sites, and the greatly superior and more mesophytic vegetation carried by the inselberg despite a very high gravitational loss, are probably the first anomalies thrust on the notice in the Sudan plains.

The larger hill masses provide a very great variety of conditions with regard to soil moisture, all or almost all of them superior to those of the surrounding mature plains or even to those of adjoining well-watered but clay-filled valleys. In these hill areas, erosion is so rapid that the successions, both of soil and of vegetation, are traceable to the eye, and it is doubtful whether any hill condition where burning occurs is stable enough to be regarded even as a sub-climax either of soil or of vegetation.

The sands of Kordofan, however, develop to a terminus which is a flat sand plain of very low and apparently stable clay content except in major hollows and the condition of these sand plains is probably to be regarded as a sub-climax condition.

Similarly, the red ironstone area, save on its steeper slopes, is in a stable condition by comparison with the hill soils and in parts would justify a similar description as sub-climax. That the mature clay plain is the ultimate fate of the hill masses given adequate rainfall, and of the ironstone plateaux given time, is borne out by a study of the clay content increase in soils of any of these zones wherever water in addition to their rainfall gets on their surface.

/Sand hills,

Ironically, judged from the datum clay content, these sands and ironstone soils are all pre-climax soils, and as such offer to plants favourable water conditions save in cases of extreme gravitational loss, e.g. acacia mellifera on Nuba Mountains shoulders, and 'safai' (eroded) areas in ironstone country, both areas of very rapid surface run-off.

A parallel example of extreme vertical gravitational loss, resulting in a pre-datum soil with a [illegible] below the mean on account of percolation losses, is found on new dunes sites.

It is suggested that a comparison of clay content of soils in terms of their present rainfalls, over continents instead of provinces, may reveal a datum on which climatic changes may be judged, and that, for instance, the relatively high clay contents in present extreme low rainfalls in parts of the Northern Sudan are in themselves evidence of previous wetter climates at these sites.

The conclusions reached regarding datum soils and their tree vegetation on Sudan facts may be summarised thus :-

A. The Climatic Normal Clay Content.

The clay content of soils on mature clay plains bears a relationship to the amount of water which the soil surface of a soil of the dry tropics receives, and this relation approaches a constant for a given rainfall when the soil absorbs and holds against gravity the whole rain precipitation on it but receives no other water.

B. The Clay-water Line or Rainfall-Texture Line.

Where a series of species form successive belts distributed across uniform mature plains according to the amount of the rainfall, and thus parallel with the isohyets, the medial zone of each species belt may be taken as the optimal site for that species. Then divergence in clay content of other datum sites carrying that species, from the clay content of this datum, is found to be compensated in terms of water and vice-versa.

A species has no rainfall optimum as a species and its rainfall requirement for a given datum soil is a determinable function of the clay content of that soil. Likewise its soil requirement measured as clay content on datum soils for a given rainfall is a determinable function of that rainfall.

C. A study of sheet slope sites losing part of their Rainfall by run-off.

(i) The Darfur Terrain.

Sheet slopes form type A of the Site and Contour -

/transect..

Ironstone. (Plate III, see also the analysis of Ironstone. Type 2 does not include rocky hill surfaces. Smooth run-off slopes are more common and varied in Darfur Province surrounding the foot-hills of the Jebel massif, an area relatively young in erosion, than anywhere else in the Sudan.

Mature clay plains are common in many parts of the Sudan. But in Darfur, a province as large as France, these plains are to be seen forming relatively rapidly before the eye, and a study of the process in Darfur has been found to assist in an understanding of what has occurred earlier in other parts.

In Darfur the terrain is dynamic. Rate of change is so rapid as to call attention to the differing stages of the process and to the order in which they follow one another.

This province, with its massif has not escaped invasion of sands which came from the north (it is believed in dry quaternary times), ~~when a period believed in quaternary times~~, when a period of greater desiccation, than now prevails, facilitated their southward progress. The sand invasion was split by J. Marra. Sands penetrated its north eastern valleys reaching, for instance, at least as far into them as J. Tormsi. (Latitude 13.45', Longitude 24.37'.) where, incidentally they are the sites favoured for cultivation, being almost entirely cleared for this purpose.

In Zalingei District the sands from the north are not well represented this area being in the sand - wind shadow of the massif.

To the east of the massif they run south as far as the Bahr el Arab flood plain which they may have crossed. In many countries an all-powerful climate produces from many beginnings a red 'ironstone' end - product and it is worth wondering whether certain of the 'ironstone' types of Nuba Mountains and of the south bank of the Bahr El Arab are not in fact the product of the climate working on now compacted, but in origin aeolian, deposits. The main south running tongue of sand is the Maalia goz, which includes Taweisha, with Abu Gabra as its western boundary and Ogr on its eastern edge.

This goz or sand dune of enormous extent, carries a north pointing salient of southern tree species, and it it the most significant soil feature of the eastern parts of Darfur. To the west of the massif, on the Zalingei-Geneina road, the sand - shadow gives place to sand again as Geneina is approached. In the area sand collars round hills become again noticeable as in northern Kordofan. It is on sites where the indigenous formations are <u>not</u> masked by the invading absorptive sand, and on the sands where human interference or climatic causes have initiated movement of water over the surfaces, that the variations in site type are found which are recognized and named by the local inhabitants, Arab and Fur.

(ii) The

(ii) The position of sheet slopes in the Darfur Katena.

In an analysis of Darfur sites outside the sand blanket there can be distinguished :-

A. Original sites
(a) Mountain sides.
(b) Lower hill and shoulder water-sheds.
(c) Out-crops on which soils do not rest.

B. Secondary sites
(a) Smooth lower slopes, usually of loams, receiving, and formed of, detritus from above. Owing to their smooth uniformity of surface, and to the type of erosion on them, these may be called sheet slopes.
(b) Valley and runnel beds also receiving material from above and around them.
(c) Valley mouth deposits, e.g. fans, cones and deltas.
(d) Valley soils now lying above the level of all but the highest floods.

C. Terminal sites
(a) Plains deposits, ultimate and almost horizontal plains of dark cracking clay soil.

(iii) Classification of sheet slopes.

Of the above sites, the secondary sheet slopes cover [illegible] areas and reveal, within their own category, succession features (both as to the nature of their soil surface and as to the species they carry) of great significance. In Darfur these sheet slopes are given locally the name 'nagaa' and they are further characterized by the local inhabitants according to the predominant tree species which they carry for the time being. Thus they are :-

(a) Anogeissus schimperi 'nagaa'
(b) Boswellia papyrifera 'nagaa'
(c) Terminalia brownei 'nagaa'
(d) Lannea sp. 'nagaa'
(e) Acacia hebecladoides 'nagaa'
(f) Albizzia sericocephala 'nagaa'
(g) Treeless 'nagaa' called 'tewara futuh'

(iv) Succession on sheet slopes:

The process starts in Anogeissus schimperi forest. This is perhaps wrongly included as 'nagaa' since, in its undisturbed state, it still carries good soil. This species has a relatively high moisture demand and on the J. Marra slopes it is vulnerably far north of its optimum occurrences. But it is the starting point of the fatal succession of changes, all in

The direction

the elimination of [illegible] vegetation. The area of slope which [illegible] by carrying A. schimperi passes thence to a condition in which it carries [illegible] and thereafter the other progressively drier species in the order listed above until it becomes [illegible] the treeless 'nagaa', a soil-less hard sheet over which the rainfall rushes with so little penetration that travellers, caught without shelter on such an open area, dig a hole in the earth and bury their clothing to keep it dry until the storm has passed.

In this succession it is patent that the process is one of retreat. If it were a feature shown by two species only with the presence of seedlings of one species occuring under old trees of the other this would be suspect as evidence of retreat.

The margin of difference in water needs between one species and the neighbour in the belt transect is usually narrow.

But where, throughout a whole Katena of species, each species of the series is replaced by a neighbour of the belt transect and invariably by the same neighbour, and where this progression leads albeit through moisture differences individually narrow, from a species notoriously water - insistent (Anogeissus Schimperi) to one of higher thirst tolerance (Albizzia sericocephala) and thence to the tree-less sheet slope, there can be no alternative to the admission of retreat.

So it is with the succession on sheet slopes. This is no case of a gradual succession of species on a stable soil. It is a succession occuring as the soil changes, and caused by the impoverishment of the soil of each given site. It is not only an example of plant succession, it is case of soil succession also.

Thousands of square miles of soil, all these slope soils in fact, are passing rapidly away each to the next poorer type of soil. They are passing so rapidly that it is doubtful if more than one generation of a given species ever occupies a particular 'nagaa'. To the casual eye there will be found constancy in proportion of species for generations. Indeed, looking over a wide enough area, without major climatic changes the vegetation will remain nearly constant for many centuries as regards total areas under particular species. But these total areas will appear on constantly changing surfaces. As an area passes out, by erosion, from the class of site which can grow Anogeissus schimperi and becomes fit only to grow another and a poorer drier species, so also will some upper area of this mountain mass enter the class of soils capable of growing Anogeissus.

Mountains are areas which have resisted erosion more successfully than other parts of the crust and not until they have been eroded to the extent of losing their features will

/those further

these harder hills [illegible] to provide sites for each of the [illegible] = sen [illegible]. But even their gentlest slopes [illegible], [illegible] consistent constancy in composition over [illegible] allowed to conceal an equally constant and persistent [illegible]tion throughout, in which each zone is rapidly passing [illegible] the scale of nominads to end in [illegible] 'upper' or 'lowers Cutch'.

It would probably be natural to seek to reduce these [illegible] to a net balance over the province as a whole, [illegible]. If so the net loss cannot be placed at more than so many feet of high land exchanged annually for so many acres of [illegible] plain. Were springs and hill streams not dependent on the [illegible] of this procession of retreat, is a hill slope better than a clay plain?

D. Some agricultural soil types

This whole region is essentially one of soils in very varying degrees of maturity, maturity being taken as represented by the cracking soils of the clay plains. When a choice of soils exists as here, it is invariably to be noted that each crop species is given its own particular type of soil. This has a vital bearing on the prospects of settled husbandry in that crop rotations could only be practised by growing a species on a soil not held, by experience, to be the best available for it.

A short series of samples was taken to show the physical soil types preferred for earth-nuts and 'mareig' millet.

In a given rainfall earth-nuts are sown on soils of 15-2[illegible]% clay content, mareig millet is sown on soils of 11%-25% clay content, sesame is sown on soils of over 30% clay content.

PART III - CHAPTER II WATER LOSS AT THE SOIL SURFACE.

The value of the clay content as an indicator is in close relation with its influence on rate of water movement in the soil (48 p. 70). It appears that it is what is lost at the surface of clays, and not what is originally available in them, which is of importance. A soil may be wet for a ninety day millet but dry for a 365 day tree.

Great attention has been paid by many workers to the measurement of the evaporating power of the air by atmometer readings in various plant communities and at places in various successions.

Using these data the evaporating power of the air in its action on the leaf surface has been studied (vide Maximov) in great detail, and evaluated as a habitat factor.

Much less attention has been paid to the reaction of a variety of soil surfaces to the evaporating power of the air. (Meyer 101).

It is known that the climatic climax clay receives and holds against gravity the whole precipitation receipt. Why is it not more productive in terms of vegetation? Why is there to be found, typically, on adjoining pre-climax soils, (those which have suffered loss by percolation and by surface movement, a much more mesophytic vegetation, a vegetation with a much higher moisture demand, a vegetation with a much superior growth rate?

Transeau and Meyer (5 p. 143 et seq) have studied distribution in terms of evaporative power of the air and have endeavoured to drive a relationship between precipitation receipt and evaporative power of the station which shall be in index of the water relation of the station.

But high evaporative power acts on soil moisture not only through the plant by transpiration, but also directly on the soil surface particularly in countries of seasonally naked soils and the response of soil surfaces to evaporative power varies within an enormous range particularly in the dry tropics.

In a sand, a loam or an uncracked clay the soil-air surface may be relatively small in relation to the leaf surface of a crop growing on it. But in heavy clays which crack (in some cases to a depth of 12 feet vertically) and are then further comminuted in a cubic or hexagonal complex according to their composition, the soil-air surface progressively exposed is very many times the leaf area of any low-growing surface crop on it, and the soil-air surface loss greatly increased. The

/mulching of

mulching of tropical clays (and even of temperate soils for certain dry conditions) is still the cultivator's practical safeguard against a loss of soil water due rather to evaporation at the soil-air surfaces than to evaporation of soil water via the leaf surfaces of a plant growing on it. Keen's conclusions are not yet acceptable on the cracking clays. The Sudan soil chemists have shown (68 for 1928/29) that Gezira clay soil, maintained at 30% moisture, lost water at the rate of 34.2 tons per acre in 24 hours on 29th-30th April 1929.

It will be seen that Transeau's precipitation-evaporation ratio (5 p. 143) cannot be a true measure of soil-water value for all clay contents at any one station, but is merely a station's climatic mean. In terms of the theory set out in this paper it has an absolute value for one soil and for one soil only at that site, and that soil must be the soil of climatic climax clay content for the climate in question.

In dry tropical conditions at least, the station value of the precipitation-evaporation ratio is a function of the soil of the site and the ratio is not a factor equi-incident on varying soils.

In the dry tropics the precipitation-evaporation ratio is of the most limited value save where considered in terms of the soil surface receiving the precipitation and yielding it to evaporation.

Not only the conditions under which soil water is removed from the soil through plants living on it must be considered but also the conditions under which the evaporating power of the station removes, <u>at soil-air surfaces</u>, a proportion of the precipitation receipt which is thus never after available to the plant population, even if it originally existed in the soil as chresard and not as echard.

This is a most important loss in the cracking tropical clays, and falls to be added to their high echard, if indeed it does not include part of the echard. It is a loss at the expense firstly and mainly of the chresard. The holard has a falling value throughout the dry season until the soil yields no more water to evaporation. This occurs when the echard, <u>which began as the soil moisture held by the clay against the plant root has been reduced to the soil moisture held against plant root and against loss by evaporation at soil-air surfaces</u>.

A similar criticism must be levelled at Meyer's "N.S. quotient", the precipitation-saturation deficit of air (5 p. 143). While of some use as an expression of factor change over widely scattered stations, it takes no account of varying soil surface response to evaporative power.

/Further,

Further, neither Meyer nor Transeau in their ratios appear to take account of the inefficiency of that part of precipitated water lost as gravitational water whether by surface flow or vertically. If in the ratios of Transeau and of Meyer, for total evaporation measured in the air there were substituted total soil water lost by evaporation at the soil surface of the datum soil a truer expression would be achieved of the habitat value of evaporative power expressed as a mean for that station.

If the soil is not a datum soil further allowance for gravitational loss or receipt is necessary before the ratio can be used as an index.

Save for datum soils, either ratio can only be a station mean and within even the most limited station zone there will be represented pre-datum, and post-datum soils on which the evaporative power will produce such a diversity of response, measured as soil water lost to the plant population, that the ratio representing the mean will serve, on these soils, as no more than a base line for the measurement of local divergence.

In summary, in dry tropical conditions at least, and recalling the loss of 34.2 tons of water per acre in 24 hours from a 50% clay, it is not the evaporative power of the air acting on the perennial plant which is the important factor in the soil-water relation, but the response of the soil direct, through the soil-air surfaces, to the evaporative power of the air. This response of the soil varies with its clay content more than with any other property. The clays dry out, the sands remain moist at 22" after the fierce heat of a Sudan summer. It is not improbable that black cotton soils, by reason of their colour, reach higher temperatures than lighter coloured sands, to the further detriment of the water supply in these tropical clay soils. (5 p. 219).

Clements conceives of normal succession as leading from a hydrophytic or xerophytic extreme towards a mesophytic climax. The protection of clay surfaces by vegetation or by sand initiates the first stages in that direction on clays.

In Sudan conditions, the blanketing (by vegetation) of a clay soil which, bare, loses moisture rapidly at its soil-air surfaces, makes progressively more of the holard into available chresard by reducing or delaying soil surface loss. From practical experience it appears in field conditions in the dry tropics that the essential first step towards mesophytism is surface protection to reduce surface evaporation. Blanketing of a heavy clay by drift sand produces the most remarkable increases in growth rates. Examples of this are to be seen in the Acacia arabica plantations at Gebel Bouser and Gamueia. In the former, surface drift sand carried on the south wind and trapped by the southern fringe of the

/plantation has

plantation has doubled the growth rate of the trees whose cracking clay soil was thereby mulched by sand. At Gamueia, sand was driven in loads to the clay lands to make a germination bed in each seed hole dug in this raw cracking clay. The sites of sand dumps have produced, in 4" - 6" of remaining sand lying over the clay, a doubling of the growth rate during the first two years.

PART III - CHAPTER III THE CLAY WATER LINE OF A SPECIES, WITH EXAMPLES FOR TYPE SPECIES.

Thus far an attempt has been made to show :-

(i) That the clay content of soils bears a close relationship to their surface water receipt. As soils approach the condition of the mature clay plain this relationship becomes a relationship with the rainfall, the clay content becoming more closely dependent on the precipitation receipt, and establishing the balanced soil condition which ~~we~~ has been called the datum clay content or climatic normal clay content. Pre-datum soils are formed on areas absorbing and holding less than their precipitation receipt, and post-datum soils result from conditions in which the total receipt exceeds the precipitation receipt.

(ii) That the distribution of species cannot be interpreted in terms of surface water receipt alone, that the individual species is versatile in respect to surface water receipt. (By surface water receipt is meant the total water received by the soil surface).

(iii) That the individual species is versatile also in terms of the clay content of the soil it grows on. These facts turned investigations along two lines, first to a search for the moisture optima of given species, the discovery of their moisture sequence, and to the study of the mechanical attributes of their soils; and secondly, and temporarily, back into the clutches of Schimper and his theory of physiological drought. It has to be assumed that different species have different moisture requirements. The facts that clay soils in 500 mms. of rainfall in the east carry species which need only 300 mms in the sandy west, and that 500 mms. of rainfall in the east supports completely different associations to those found on that same isohyet in the west, had to be explained. Fortunately, perhaps, the soil differences were so outstanding as to point the way. In the west are red sands of very low clay content, 5% to 20% being a common range; in the east dark cracking "cotton" soils of 50% clay and over.

On which of these soils is to be decided the rainfall optimum for a given species, and how are comparisons made of the moisture demand of one species studied on clays with that of a second studied on sands? Obviously a clay content datum line is necessary if the moisture requirements of species are to be compared. The next difficulty is this : that clay contents increase with rainfall, and that on any one clay content not more than one or two of the type species are to be found at any given rainfall. It is necessary for the determination of the rainfall requirement of a species to find the centre of its belt occurence, and to determine also

/the clay

the clay content of the typical datum soil of its rainfall belt occurence. On this datum other soils and their rainfalls can be evaluated as sites for that species.

As already referred to in the eastern Sudan, from the latitude of Aroma near Kassala southwards to Roseires there is a line approximately 300 miles long running from the 300 millimetre isohyet to the 800 millimetre isohyet. Along this line no marked variation in type of soil occurs such as the sand invasion which has broken up the soil distribution of Kordofan. The distribution of the rainfall belts of species along this eastern Sudan line has been adopted as indicating their relative moisture requirements. These belts are on a continental scale. Increasing clay content accompanies increasing rainfall, but not at such a rate as to produce uniform conditions of available water throughout.

The sequence of the Acacias on this line has been given in Part II Chapter II A.

Having accepted this moisture sequence and noted the apparent anomalies, an explanation had to be sought for the distribution of drought resisters in apparently well-watered sites and of mesophytic types on bare dry-looking hillsides, evidence for and against Schimper's distinction between physical and physiological drought was sought. After the most careful ~~careful~~ consideration of local distribution in the light of Schimper's theory the writer has had to abandon it as being incapable of explaining the Sudan facts. It may not be out of place to record the conclusions formed during the attempt to apply the theory to the Sudan facts.

Schimper's classification of drought as physical or physiological is reducible into a distinction between drought in the soil and drought in the plant.

In the moisture economy of dry tropical plants there can be no drought which is not physiological and there can be no drought in the soil which is not physical. A soil apparently abounding in moisture may yet be physically dry in the sense that much of its moisture is "held" as by clays, against root suction; or it may be physically dry for vital periods although excessively wet at others. Many soils, also, from superficial examination are assumed by some observers to be dry sites, which, in fact, offer favourable moisture conditions to plants, e.g. sand-dunes which the Sudan experiments with Prosopis juliflora and sakellerides cotton have shown to be the moistest sites in the ~~se~~ in contour transect.

A plant may be suffering from drought in a truly wet soil. When this is so, the lack in the plant is a physiological lack as are all droughts in the plants, but the soil is seasonally physically wet and only physiologically dry at certain seasons.

/In short,

In short, Schimper's classification is a confusion in, and a cross-borrowing of, the terms descriptive of the processes which pertain to the soil, and the processes which pertain to the plant. The wettest clay at one season is, at another, physically and physiologically one of the driest soils occurring in the dry tropics.

The surface losses of clays, by evaporation, produce their soil drought. This condition is most extreme in the heaviest clays. The amount of precipitations on them is little index of their eventual chresard, and the precipitation receipt has a growth value which falls as clay increases, though at a very slightly less rapid rate.

In pursuit of the main enquiry, several series of soil samples were taken on typical datum sites of several type species under widely differing conditions of rainfall.

Surface inundation is a factor not so far measurable, and neither inundated nor run-off sites have ~~not~~ been used as stations in the determination of clay-water lines. The interesting task of deducing the growth value of inundation water by comparison of inundated sites of known receipt with rain areas carrying the same species is dealt with in Part III - Chapter IV.

In the selection of sites to determine a clay-water line or rainfall soil-texture rates, they must, until inundation, can accurately be assessed, be sites in receipt of rainfall only, and sites not subject to gravitation loss. The site which receives more, or retains less, than its precipitation receipt is of reduced value as a species station unless there is a means of measuring the surplus or deficit, and of evaluating the clay formation effect of the excess or deficit.

From the clay contents of these sampled sites and from the rainfall values for the areas sampled diagrams have been prepared which show the nature of the relationship. It is obvious that the lines given in the diagrams are not final determinations for the species concerned. As more material becomes available for the Anglo-Egyptian Sudan a closer approach to final accuracy in the determination of the clay-water lines of species will be possible.

It is already patent that the clay-water relation will be represented by a ribbon or band (see Plate XXII for *A. seyal*) and not by any narrower line. The width of this band, given proper assessment of sites, will be the true measure of versatility of species in terms of the dual factor.

From the four species diagram Plate XXIII the clay-water lines appear to form a uniform pattern so far as natural sites are concerned. The line for *Khaya senegalensis* in the same

/diagram

diagram illustrates the great increase in range which artificial regeneration makes possible for this species, in comparison with the natural zones of the others shown.

A further problem for study is that of the clay-water line for one and the same species in different climates. Judged on species, very similar conditions to those of parts of the Sudan appear to exist in South Karamoja, Uganda. (25). The Sudan shares Capparis decidua with many countries. How far its clay-water line determined for the Punjaub plains will agree with its Sudan line is a matter for study on a ~~water~~ wider scale than is open to the writer.

The difference between the precipitation-clay ratio in the Punjaub and in the Sudan Gezira has been referred to above. Whether the clay-water lines of particular species growing in both areas coincide, cannot, as has been said, be determined by the writer. It is suggested that if they do not, the reason for the difference is to be sought in adaptation and in the developement of territorial sub-types of the species.

In some cases equivalent but different genera and species will be found. The South American equivalent of the Acacia mellifera appears to be the Prosopis juliflora, possibly with even smaller moisture demand.

PART III - CHAPTER IV. PRACTICAL APPLICATIONS OF THE TRANSECTS AND CLAY-WATER OR RAINFALL-SOIL TEXTURE THEORY.

A. The choice of a site for its soil texture, knowing the rainfall; and the evaluation, in terms of available growth water, of the various site types in a particular rainfall.

(i) Uses of the Transects.

When, from analysis of the records made of natural occurences of all the various species dealt with, the fact emerged that they share a site transect of a common form in their distribution across the isohyets, a startling revaluation of sites in terms of available growth water in them became necessary and possible. In brief, whereas previously the low-lying hollows in which water accumulates had been regarded as sites likely to be favourable for moisture, it has now been shown that high-lying sands and grits, and even rough-surfaced hill-sides, though they may lose part of their precipitation receipt by run-off, nevertheless constitute the moisture-optimum sites for perennial plants in the Sudan tropics.

The subsequent preparation of the belt transect, the transect which is simply the list of the type tree species in the order of their moisture demand, and which was compiled also from the records of distribution on comparable sites, provided a simple key to growth moisture evaluation, in the quantitive term, of the various sites in each rainfall which still carry natural tree vegetation. Where such vegetation is absent, the terrain can still be evaluated, though less precisely, by use of the site transect, and, in the case of sites approaching datum sites, with great precision by determination of the clay-content.

The practical application of these methods to the reafforestation of sites in penultimate desert has produced results in rainfalls previously considered hopelessly low for tree growth.

Before the advance of populations it is the most valuable species which first disappear. Where, as in the Sudan, the increase of population has struck at natural vegetation from the dry end, man shares the blame with such changes of climate as may themselves be producing retreat. However, since this discovery of the relative value of sites showing the high water availability of sands and grits and hill sides, it has been made obvious that, while man has removed completely many of the most valuable species from whole belts of latitude in north Africa, yet since the species have their termini now on site types far from the true terminus of the site transect which all species share, they can, therefore, be restored northwards again.

/There is

There is at least no climatic obstacle to their restoration. The central latitudes of the Sudan are, in fact, seen to be reservoirs of species which still exist there on medial sites in the site transect, although cut out by man on their dry terminal sites further north. That these dry terminal sites have suffered by denudation is not to be doubted, but seldom has their clay-water relation been radically changed for the worse. Where it has changed it has been shown that only the crudest methods, as for instance sand-trapping on their surface, are necessary to ensure the growth of species long since lost from these areas. In fact, although the rainfall cannot be controlled, in many wind eroding areas surface texture can be controlled to increasethe water available. The species are now known which may be taken from this reservoir of species persisting on their medial sites, for translation northwards and restoration to their terminal sites, and, what is still more vital, the sites in the north on which they can be re-established are at once known when the clay water line, or even only the heavy rainfall vector of that line has been determined for the species. Knowing the heavy rainfall vector of the species, the missing dry end can be interposed from a knowledge of the clay water lines of the species itself if its line is known, or from the clay water lines of known species adjacent to it in the Belt Transect.

(ii) Treatment of Desert.

The following paragraphs define the stage which has been reached (in June 1939), in the afforestation of penultimate desert in the 150 mms. isohyet by the application of the clay-water theory.

The objective is the afforestation, on an economic basis and under rainfall only, of non-riverain land in the 100 - 300 mm ~~4-12"~~ isohyets of the country.

The work is primarily of interest to those living under the lowest rainfalls in Africa, but it cannot be without significance elsewhere, and the fact that it is being carried out in country which carries Capparis decidua, Salvadora persica and Calotropis procera as three of its commonest bush or scrub species makes it possible that it will also have a limited interest in Indian semi-desert conditions.

So far as the Sudan is concerned, the results described here are the only suggestion which it has so far been possible to offer with any confidence towards the problem of erosion in those areas of the country which are so dry as to be incapable even of growing enough grass to give themselves a fire problem.

The sovereign, and, as yet unattainable, first remedy for erosion in the 250 mms to 1500 mms rainfalls is fire protection. It may be that a solution is found for semi-desert conditions long before a solution has been found for the wetter areas which support inflammable grasses.

/In these

In these Sudan latitudes of low and capricious rainfalls, it had long been counted natural, especially after some initial success with <u>Acacia arabica</u>, to concentrate plantation trials on lands which received water from river floods, or at least from that unabsorbed rain which came to them as run-off from neighbouring soils. That is to say, efforst had been concentrated on soils whose surfaces received more moisture than was attributable to the rains falling directly on their own surfaces.

The extremely slow growth rates of indigenous <u>Acacias</u> (<u>tortilis</u>, <u>raddiana</u>, <u>flava</u> and <u>orfota</u>) on the sites to which these spcies had by then been reduced, pointed to the reafforestation of rainland in this latitude and rainfall as being an uneconomic and hence an impossible task. But further riverain land near the towns was not available for further plantations of the flood demanding <u>Acacia arabica</u>. At this stage, extremely sandy soils such as dunes and high ridges were, by tradition, dry sites, and it must be confessed they were accepted as such. The tradition was not entirely an imported one, but it was not realized that local cultivators could find, at one season, maximum moisture conditions on the same soils which, at other seasons, were sites of minimum available moisture. The difference, that is to say, between the site conditions adequate to the needs of a 100-day millet and those demanded by a 365-day tree had not been appreciated. So also, species occurring on the soils wrongly regarded as dry soils were equally inaccurately evaluated interms of relative moisture demand.

As the work, described in this paper, on the distribution of tree species throughout the whole Sudan progressed, it became apparent that indigenous Sudan tree species have their most northern natural occurrences, (their occurrences in lightest rainfall) on sandy or rocky soils and never, by any chance of nature, on the heavier clays.

Plant thirst in perennial plants is particularly noticeable on clays liable to, and probably owing their existence to, repeated seasonal inundation by standing water. But it is by not means confined to inundated clays, being noticeable on all clays.

These simple facts, of which it is suggested the ultimate significance may be far-reaching in several climates, enabled a corrective review to be made of all the experimental afforestation previously attempted here under rainfall.

Among other results, a series of unsuccessful attempts to afforest sites in wet-looking clay-desert country receiving, from run-off, the physical equivalent to many inches of rainfall, was abandoned. Resort was made instead to sandy ridges, even

/to those

to those whose slope and surface skin encouraged run-off and thus cheated the under layers of part of the ever-meagre rainfall which falls on them in this latitude.

In the attack on the sands the most valuable assets have proved to be :-

(a) A species introduced by R.E. Massey, formerly Government Botanist here. This is the mesquite of South America, Prosopis juliflora.

(b) A well-proven technique in the use of pot-raised seedlings as transplants.

The mesquite (Prosopis juliflora) gives promise of solving the problem of afforestation of light soils in rainfall as low as 100 mms. certainly. There are good reasons for the belief that its establishment will also be possible in rainfalls as low as 75 mms. provided that, if precipitations are restricted to this total, they are so distributed as to penetrate light sands to a depth of at least 750 mms. At that depth they are likely to effect a junction with the moisture remaining from preceding seasons.

Such soils, it has been established, are sufficiently retentive of their rainfall receipt to remain moist to the point of cohesion (when hand-pressed) at a depth of 400 mms-600 mms. at the end of the extreme drought season which culminates in late May or the early days of June. Above this depth they are dry by then. Below it they are still moist.

A further vital value of this species lies in the fact that its foliage, in all but the earliest stages is*~~good~~-proof. The beans of the tree have a very high fodder value (they are relished by horses, plough bulls, milk cows and goats), but the purely vegetative parts are apparently devoid of attraction even to the local goat, which prefers the rags and paper of the refuse hill to mesquite foliage.

(iii) Surface Improvement.

No terracing, contour ridging, or other artificial water conservation measures have yet been resorted to in plantation work on the sands save experimentally. Up to date they have not been necessary. They may yet prove necessary on small but stubbon failure patches where the rains have not percolated, probably because of already existing 'skin'. Such 'skin' forms even on sand ridges, at a rapidly cumulative rate wherever water stands on, or moves over, the sandy surface. 'skin' is the most important adverse factor, since it not only prevents percolation, by facilitating run-off, but appears also to increase soil-moisture loss by evaporation, at the soil surface, of water raised from the lower layers. This water

* Goat

/does not

does not rise to a surface of loose sand, to the same extent.

The invariable occurence of drought conditions where a clay layer overlies sand, conditions not existing on the same sands where they have no clay covering, forces the conclusion that a clay layer can dry out sands lying below it.

In semi-desert conditions it is becoming increasingly clear that the surface improvement and protection provided by the first established vegetation rapidly render such areas of skin surface absorptive by the simple process of covering them with a trapped layer of absorpitve wind-delivered sand.

At the moment, the greatest influence for good which the increasing vegetative cover is exerting on the experimental areas where it can still be controlled is this accumulation of wind-rolled sand. This sand is rolled into the fenced areas, and while, in the earliest stages of these areas, strong winds are still able to roll much of this sand right through an eight acre plot and out at the other side, yet an increasing amount of the rolled sand is being trapped by the growing young trees and by the Panicum turgidum grass. With closure to grazing this grass develops, in six months, into a factor of still more vital importance as a sand trap. Incoming sand, if it can be trapped is the best remedy for 'skin', and so far from being a threat to the plantation, it is a condition greatly to be desired in areas under proper management.

Only on those cases where seedling pot transplants are used at too young or too delicate a stage, when their bark is not yet tought enough to withstand the attrition by the low-moving sand, is it doing damage in controlled areas.

Even with small seedling transplants a stage of resistance is normally reached within two months after transplanting, that is to say before the season of severe drought and drift has set in.

Complete immunity to losses by attrition demands the use of pre-hardened transplants which are produced by adding the methods of the school to those of the nursery. The use of pot transplants enables areas to be planted which could never, because of sand attrition of cotyledons, be established with direct sown seed.

(iv) Condition and Treatment of Clay Desert.

The methods so far described have been successful on sands whose surfaces are receptive of rainfall, and which are retentive of that which percolates into them. In the Northern Sudan, heavy and naked clays can neither admit much water nor retain what they get against the losses due to evaporation at soil air surfaces in the climate of extreme dry tropical conditions.

/In the

In the Sudan the worst desert is clay desert. Pot transplants have failed year after year in so-called wet-clay sites. From such desert surfaces clay particles are seasonally (April-July) removed in 'haboobs' which are dust storms of the dust-bowl type. Winds during the season of high temperatures (108°-117° F. shade) lift and remove this dust but leave the sand and grit particles in an unbound state ready to be rolled by the ~~big~~ next high wind.

These sands& grits are the raw material essential in desert conditions here to any reconstruction of soil or re-establishment of soil cover, and, if these areas are to be reclothed, sand and grit must be available in accumulations far exceeding in depth the thin layers in which they are left on the surface when the dust is blown out from them.

This rolled sand and grit-material, wherever it is trapped by the walls and houses at a village, by bushy-based tree such as Zizphus spinachristi, Salvadora persica, or Capparis decidua, or by sucker thickets of Acacia albida, is by them accumulated into mounds overlying the clay flats. The 'stink-bark' of the Sudan, A. orfota is slower growing and coppice-form in growth and is less successful as a sand trap, but both this species and Panicum turgidum grass are often stages on the way to a sand layer whose depth overlying the clay is great enough for the growth of more significant species.

Near towns and villages where all other species have been grazed out of existence, Calotropis procera often constitutes the sole hope of sand accumulation.

The mounds large or small, which all these species tend to form out of rolling sand, at best only dot the surface like widely separated islands in a very empty sea of barren clay.

It has been shown that mesquite can be established on these scattered islands provided they are high enough, and reference is made below to the question of the necessary depth of sand. So far, no tree species of any value is available which could grow in 100 mms. of rain on the clay surfaces of the gaps between these island mounds. The clays must first be covered over with a good blanket of sand. In the current season, mesquite is being introduced, one or more on each island, in an experimental area chosen for its existing island mounds. The lower branches or outer stems of this species tend from their earliest years to sink to the ground under the weight of their own exuberant growth, and hence tend to increase horizontally their sand fixing radius. The outer branches of the 1938 crop are already buried in trapped sand. It will be some years before it can be determined whether mesquite by itself is capable of forming sand 'continents'

/out of

out of these mound 'archipelagoes', or whether the assistance of artificial sand traps is indispensable to ensure that the clay 'seas' between the mound 'islands' are covered by sand to a plantable depth. Where mounds are close together mesquite, on available evidence, is likely to succeed in doing so, but while its sand-trapping effect is yet to be demonstrated, its ability to grow on trapped sand in these low rainfalls is already demonstrated.

(v) The depth of sand required over clays.

In the selection of sites, there is this problem of deciding how deep a layer of sand is needed on the clay to support tree growth in this rainfall. This appears to depend on whether the condition of the clay is such that water, and eventually tree roots, can cross the junction of sand and clay and can penetrate the clay. Where this can happen a thinner sand layer will suffice.

Part of the 1938 work was on a natural sand ridge held by Panicum turgidum which has a depth of 8-10 feet of sand on its medial axis, the depth tapering outwards to zero on the fringes of the ridge where the raw clay is exposed by wind and by run-off from the ridge itself. From observation of the mesquite planted on this ridge, which averages seven feet in height growth in ten months, and in places exceeds ten feet, the fringing areas where the sand is but two feet thick are carrying mesquite which is no poorer than that growing on the axis of the ridge with its 10-12 feet of sand. The shallow fringes appear to benefit from a lateral percolation of some of the moisture which falls on the higher parts of the ridge and is absorbed there. On high ridges, particularly where these are of coarse or very recent unfixed sand, water has been shown to spread outwards and downwards through the ridge to the fringes. (The crests of very new live dunes drain too rapidly). Thus it cannot yet be assumed that two feet of sand above clay is an adequate depth in the absence of higher lying reservoirs of porous sands.

In all these sites, the impermeability of the underlying clays contributes to the retention of water in the sandy mounds and ridges which overly them.

(vi) Artificial methods of trapping sand.

Concurrently with the experiments for the planting of naturally formed mounds and ridges of trapped sand, experiments have been in progress for two years to devise the cheapest effective means of inducing sand deposit to form on unplantable clays, and so to render these areas plantable. These artificial methods are not sought merely as means in themselves, but as means which may hasten the determination of certain vital data on which to found the subsequent use of less artificial methods.

/It is

It is necessary, for instance, to know what planting direction, with regard to the prevailing winds at the season of greatest sand movement, is the direction most likely to permit of using one year's planting as the obstruction which will accumulate that minimum depth of sand on which the following year's plantation may successfully be established.

In these artificial experiments we have so far relied on close-woven fencing of split bamboo made on a "Thrift" fencing machine.

This fencing can be carried in rolls and is supported adequately by five foot posts three to four metres apart. Separate support wires are unnecessary.

In June 1938 a fence of this type was erected on a bare clay plain near Khartoum on an east-west line. In that same month, during a very heavy night of wind, 24" of sand and grit was trapped by the fence. The depth of the trapped sand decreased with distance from the base of the fence, but was roughly equal both north and south of it. At a distance of five feet or thereabouts from the base of the fence no sand had been trapped and the clay was exposed as it was over the whole area before the work started. No sand at all was trapped, that is to say, much further from the base of the fence than the height of the fence.

A second fence has then erected ten feet south of the first, the sand and grit at that season having come from the south. The new fence gathered 8" in three weeks when the rains fell and no further measurable change was noted until May 1939. By that date the area between the two fences was covered to an average depth of 20". At no time did the second fence collect such a depth of sand as was laid down in one June night in 1938 on the first fence.

In the rains of 1938 (July-October) the sand ridge then formed carried a good crop of annual grasses, the surrounding clays being grassless. It also grew _Cassia acutifolia_, _Cassia obovata_, and a single plant of _Calotropis procera_, all spontaneous appearances. The grasses, all annuals, of course died out in November, but the _Cassia spp._ and the _Calotropis_ are alive and growing well at 24/7/39, having survived the worst of the dry season.

A serious mistake was made in omitting to surround this experiment, which was laid down on the open desert, with a goat-proof fence. However, the mistake has brought out some interesting facts.

The narrow strip of grass-covered sand was soon eaten bare by goats as the rains ended and the grasses died. Its surface was broken and loosened by tramping, but from this stage, owing to the shelter provided by the fence, wind did

/not remove

not remove more sand than it brought, and the contour of the ridge is well preserved to date in the form and dimensions already described.

The grazing trouble did not end when the crop of grass had been eaten completely off the ridge. Throughout the whole of the dry windy season of 1938-1939 the fence has continued to be a collecting for dry fragments of desert grasses, all of them apparently grasses on which goats feed. They are trapped against the fence which is continuously patrolled by one of the town herds of goats. They come there each morning and eat all that the wind has been good enough to bring and the fence to hold overnight. The grasses appear to be carried from all the area within this segment of the goat grazing perimeter of the town which may be said to have a 7-10 miles radius.

What little grass from this source is not eaten at the fence is trampled to a fine chaff and mixed with the sand of the artificial ridge and is not all blown away. The ground of the ridge was heavily dunged by the goats and in a very promising condition to grow the _Prosopis juliflora_ planted on it in the 1939 rains.

There is no doubt that the continual goat traffic has been a major factor in preventing greater increase of sand and grit deposit during the dry season. Further, the blown grasses, which would greatly have improved the fence as an obstacle, were, as has been noted, otherwise disposed of. On the other hand, the dung and chaff have had some fixation value.

The mistake of leaving the experiment unenclosed has shown that twenty yards of trap fence per goat, across the wind, will create a highly-favoured grazing ground week after week so long as there are grasses blowing from the deserts around.

It is doubtful whether any clearer picture could be found to show the desperate surface conditions which have developed round certain dry tropical towns, including Khartoum.

Many directional adjustments, it will be seen, have still to be made before these methods can be applied to all the types of site capable of reafforestation by them.

It is now considered as proved that mesquite grows rapidly enough to make it an economic fuel crop for the larger centres if grown on a rotation of between 8 and 16 years under six inches of average rain on light soils. That is to say coupes of mesquite will sell for more than it costs to grow them.

/It is

It is further held proved that if the rainfall is not too heavym the tree provides an admirable pod-fodder for cattle and goats and thus a contribution to the support of the herds now responsible for town perimeter damage in the danger latitudes.

Still further it is proved that several species are capable of growing on, of improving, and of extending those patches of sandy soil in penultimate desert, which though themselves a result of primary or subsequent erosion, are the only areas not yet complately beyond restoration since they absorb and retain even the lightest of rains.

In some sites the species (Prosopis juliflora) has been escaping during the past fifteen years, that is where it has reached the fruiting stage and been unfenced. It has travelled at least two miles from its original introduction site at Shambat in 150 mms. average rainfall.

These results have been achieved by abandoning the 'wet' clays, and by resort to the sands hitherto called dry.

B. Choice of species to be planted, knowing the soil texture and rainfall.

Reference to the diagrams showing the clay water lines for the species illustrated, shows that after making every reasonable allowance for possible occurrences not represented there is for each species a very wide texture - rainfall field from which it is apparently entirely absent, and a very much narrower texture-rainfall field which is its field of occurrence: its vector. Failure evidence, in artificial afforestation confirms the restricted texture-rainfall field open to a given species. The differences in clay content between success sites and failure sites were often so narrow as to appear insignificant. Fifteen years of trial and error at Tewfikia and Zarzour reserves, to which reference has been made and at other sites, revealed that the higher the clay content (and often the inundation) the lower down the scale of species in the order of their moisture demand was it necessary to come to find a species which could survive there. Today the chôice of species whose clay-water line is known, is determined almost automatically on the basis of the texture of the surface soil at the site; and knowledge of the clay-water lines of the other most significant species is continuously being accumulated from success and failure plantation sites as well as from samples taken in antural occurence sites across the isohyets. The combined species diagram (Plate XXIII) contains species having their belt centres in the Acacia-Short-Grass-Country in the Acacia-Tall Grass Country, and in the Mixed Deciduous Forest. Reference to the position of one of these species in the belt transect shows the species most closely associated with it as regards

/clay-water

in the mixed deciduous where many species

clay-water requirements. There is great overlapping share so comparatively narrow a rainfall span.

All species share parts of their range with others, their near neighbours on the scale of moisture demand, i.e. on the belt transect, but no instance has been found of species whose dry and wet termini, i.e. whose ranges, coincide, physically or geographically. Such facts make it dangerous to deduce from the existence of one species at a given site that another known to be an associate at another point in their respective ranges will prove a successful associate at this site also. Without a knowledge of the natural occurrence clay-water line, the extension of range which can be brought about by artificial renegeration methods, methods which convert the limited natural reproduction range into the wider existence range, often masks for a time the fact that a mistakem choice of species has been made.

Each species has its two versatilities, its two spans: that within which it reproduces itself and that within which it can grow if assisted artificially through initial difficulties. The first lies within, and is a part of, the second. Failures within the wider span are failures of season, or of technique, and can be overcome. The wider field of real error and of wasted effort is that which lies outside the second span, which lies in fact in the texture-rainfall vector from which the species is excluded by the extent of its moisture demand. Knowledge of the texture-rainfall range of the species concerned at once enables this, the widest, field of error to be avoided.

C. <u>Estimation of rainfall, from natural occurrences, the texture of the soil of the site and the species range (i.e. its clay-water line) being known.</u>

The sequence of the site types on which a species exists from its wet terminus to its dry terminus has been given in Part <u>II</u> Chapter <u>III</u>. (See plate <u>XIII</u> showing site transect). The <u>estimation of rainfall</u>, from <u>natural occurrences</u>, is of much less practical value than the estimation of the growth moisture of a site in a known rainfall. At the same time, the African rainfall is not yet known in such detail or with such accuracy that the use of tree indicators for its evaluation need be despised. Further, particularly in the vicinity of the higher hills, local pockets of higher or lower precipitation occur. More mesophytic types are commonly found, for instance, on the N. and N.W. slopes of the few important massifs.

Rainfall estimation is possible with most accuracy by sampling datum soils carrying species whose clay-water line is already known. When no datum soils are available, as in many broken hill areas, it is necessary to rely on the rainfall

/transect and

transect and the site transect, and, under these conditions, for rainfall estimation, a good 'bracket' must be found. That is to say, while the hill slopes themselves offer a comparison with other hill sites of known rainfall, these are pre-datum sites only, and post-datum sites must be sought for confirmatory evidence of the amount of the rainfall.

D. Estimation of the rainfall-equivalent of surface water receipt or of loss by run-off or evaporation.

By definition, in all except datum sites, the water value of the site, as represented, for instance, by the vegetation of the site, fails to indicate the rainfall, since such non-datum sites receive and hold either more or less than their own rainfall receipt. Where the rainfall and the clay content of a particular non-datum site are known, and where there occurs on it a species whose clay-water line has been determined, the water gain or loss of the site in question can be evaluated, using this clay-water line. It is only necessary to ascertain from the clay-water line, the rainfall which corresponds on datum soils, to the clay content of the non-datum site in question, to note the difference between this rainfall and the rainfall of the non-datum site.

On sites losing water by run-off the rainfall at the non-datum occurrence of the species exceeds the rainfall at the datum occurrences of that same clay content. On sites receiving water by on-flow in addition to their rainfall receipt, the rainfall of the occurrence site is less than the rainfall at the datum occurrences having that same clay content. As an example, were Acacia seyal (Plate XXII) to be found on a 30% clay on the 300 mms. isohyet it would it would be an occurrence only capable of explanation by an on-flow receipt of water, having a rainfall equivalent of approximately 200 mms. of rainfall. Or again, if the same species were to be recorded on so light a soil as a 20% clay in a rainfall so heavy as 600 mms. only a loss by run-off equivalent approximately to 160 mms. of its total rainfall receipt could explain this record.

This fourth application of the theory has significant uses in irrigation practice. By it can be measured the extent of the large 'unused' fraction of applied irrigation water of which an example has been given for sakellarides cotton in Part III Chapter I.

LIST OF PLATES.

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" II. Sudan Meteorological Service: Mean Annual Rainfall.
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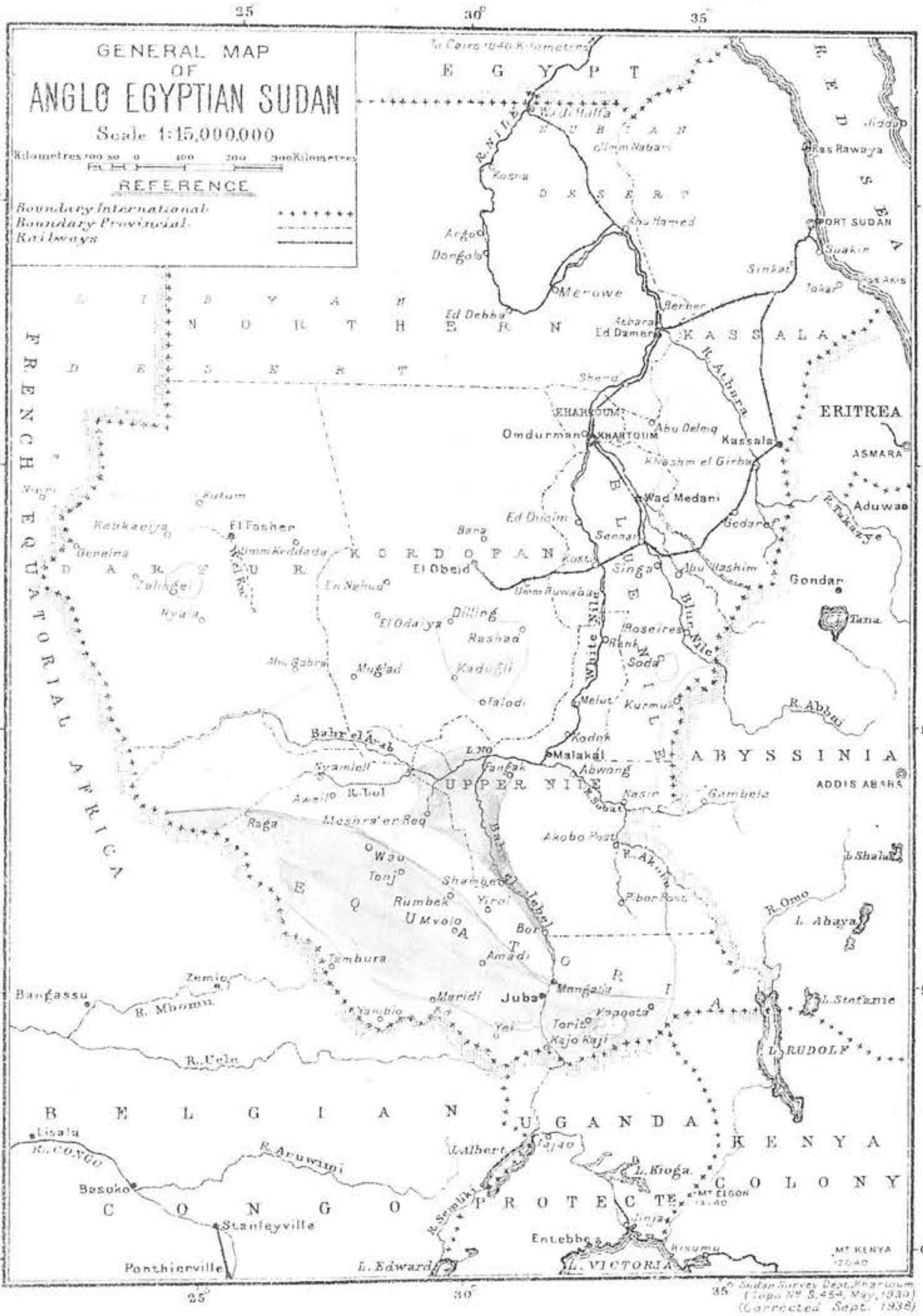
PLATE I

PRINCIPAL SOIL TYPES AND THEIR APPROXIMATE DISTRIBUTION



Hill and valley soils.

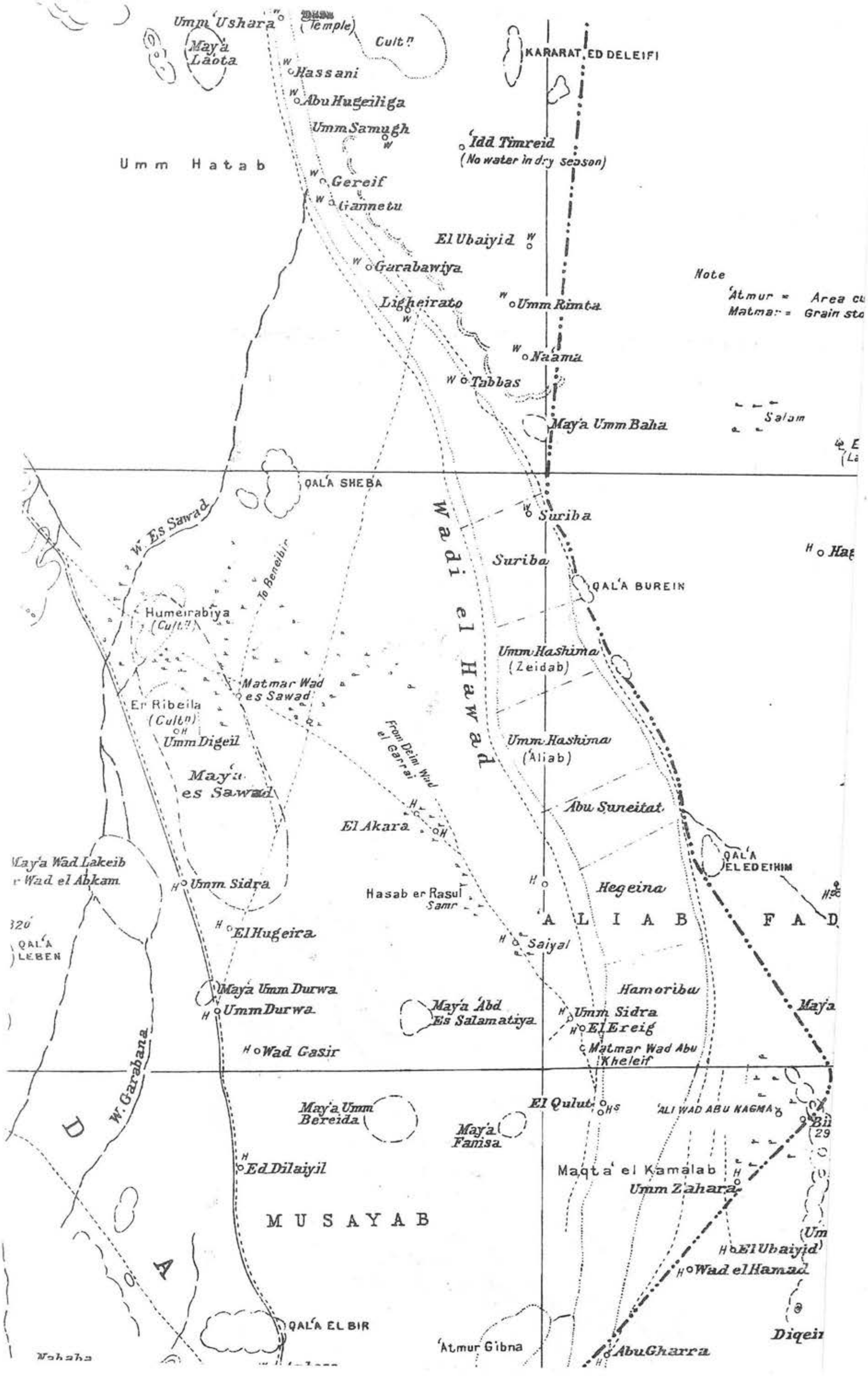
Stains of ...

The Clay Plains

Red ironstone soils

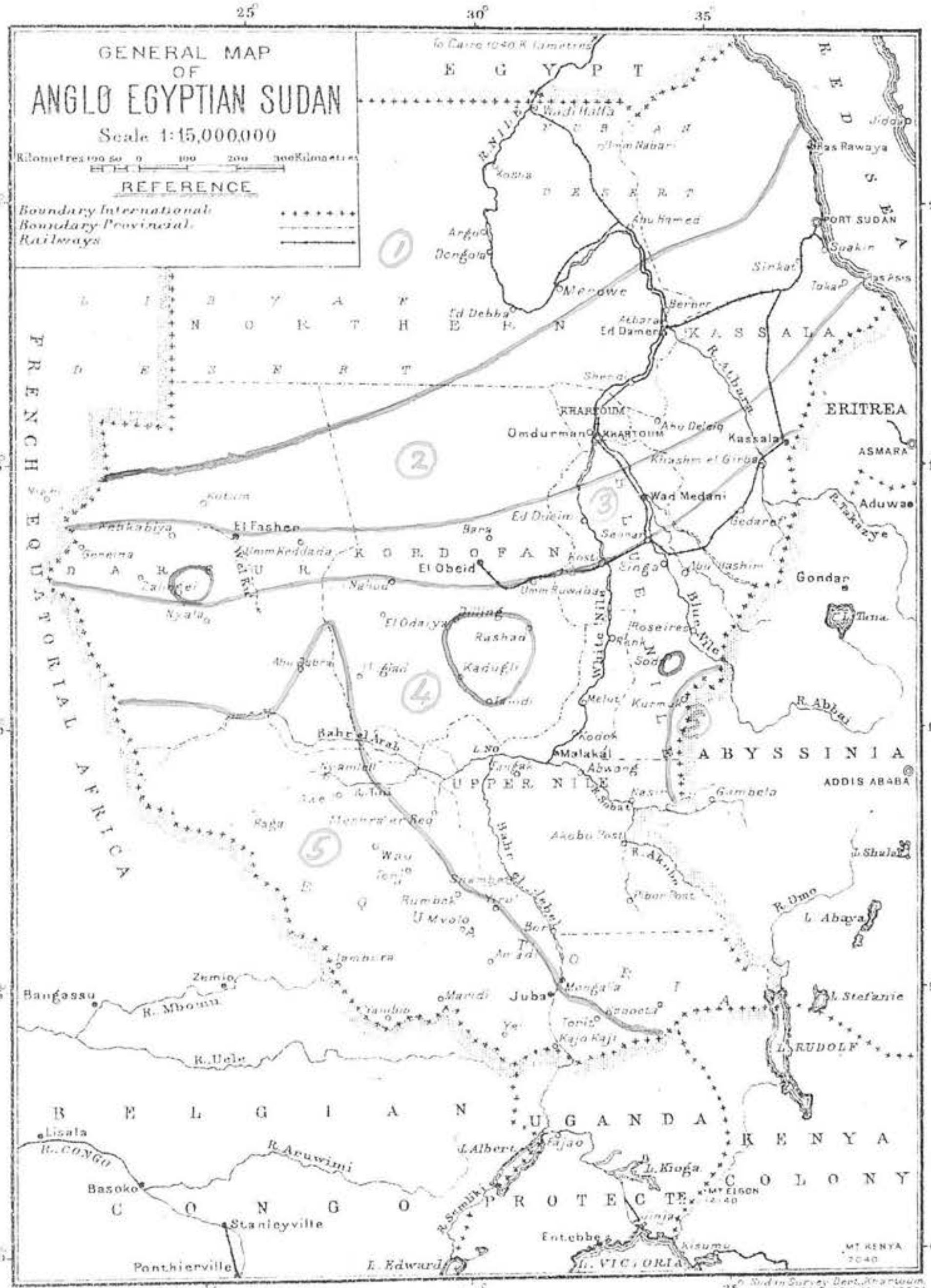
Sands, ... and old clays of the ... deserts.

The ...



Umm 'Ushara
(Temple)
Cult.n
Maya Laota
KARARAT ED DELEIFI
Hassani
Abu Hugeiliga
Umm Samugh
'Idd Timreid
(No water in dry season)
Umm Hatab
Gereif
Giannetu
El Ubaiyid
Garabawiya
Note
'Atmur = Area cu
Matmar = Grain sto
Ligheirato
Umm Rimta
Naama
Tabbas
Salam
Maya Umm Baha
QAL'A SHEBA
Wadi el Hawad
Suriba
W. Es Sawad
Suriba
Haɡ
QAL'A BUREIN
To Beneibir
Humeirabiya
(Cult.n)
Umm Hashima
(Zeidab)
Matmar Wad es Sawad
Er Ribeila
(Cultn)
Umm Digeil
From Deim Wad el Garrai
Umm Hashima
(Aliab)
Maya es Sawad
Abu Suneitat
El Akara
QAL'A EL EDEIHIM
Maya Wad Lakeib
Wad el Abkam
Umm Sidra
Hegeina
Hasab er Rasul
Samr
ALIAB
FAD
El Hugeira
QAL'A LEBEN
Saiyal
Maya Umm Durwa
Hamoribu
Umm Durwa
Maya 'Abd Es Salamatiya
Umm Sidra
El Ereig
Maya
W. Garabana
Wad Gasir
Matmar Wad Abu Kheleif
El Qulut
'ALI WAD ABU NAGMA
Maya Umm Bereida
Maya Famisa
D
Ed Dilaiyil
Maqta' el Kamalab
Umm Zahara
MUSAYAB
A
El Ubaiyid
Wad el Hamad
QAL'A EL BIR
'Atmur Gibna
Abu Gharra
Diqei

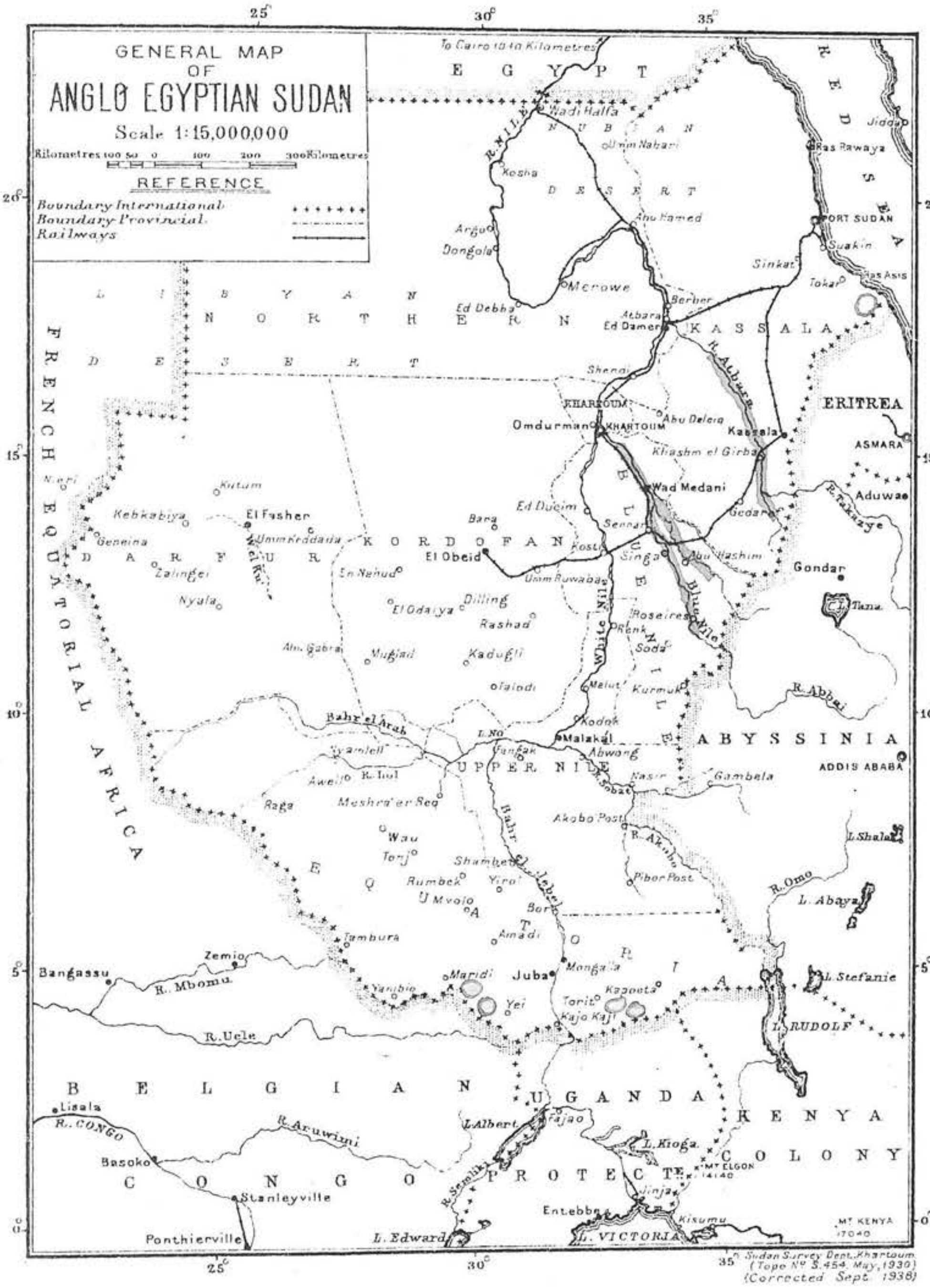
PLATE IV



Principal ecological formations
of Tree Vegetation.

1 Desert.
2 Acacia - Desert Scrub.
3 Acacia - Short Grass Country.
4 Acacia - Tall Grass Country.
5 Mixed Deciduous Fire-Swept Forest.
Hill massifs in Acacia Country.

PLATE V & PLATE VI

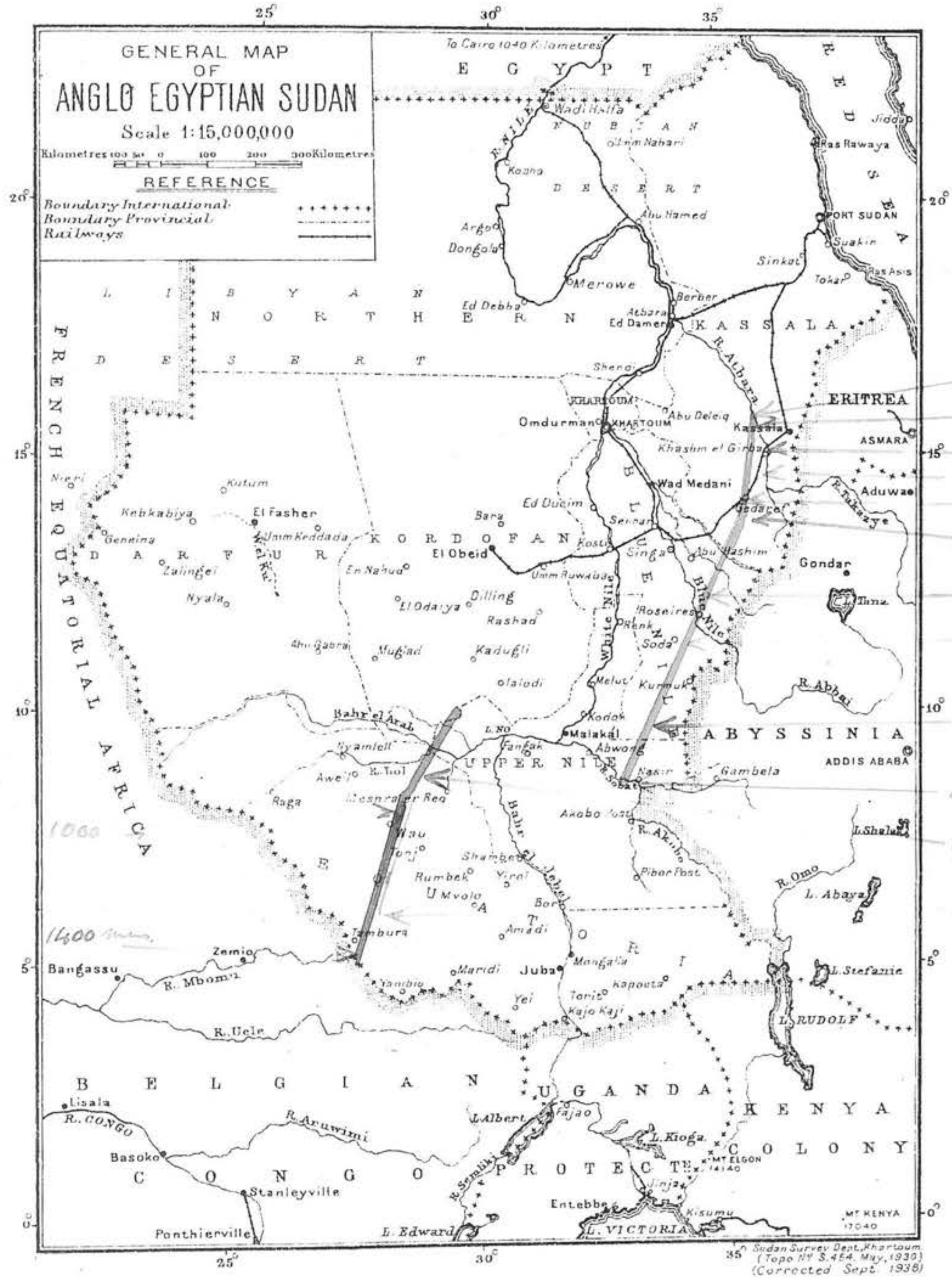


Distribution of the [illegible] resin producing Kerrib

Distribution of four small 'Bowl' forests

Only recorded Sudan occurrence of Juniperus procera, the pencil 'cedar' [illegible]

PLATE VII



200 mms

Acacia tortilis

A. mellifera

A. fistula

A. senegal

A. drepanolobium

A. seyal

A. campylacantha

A. Sieberiana

800 mms.

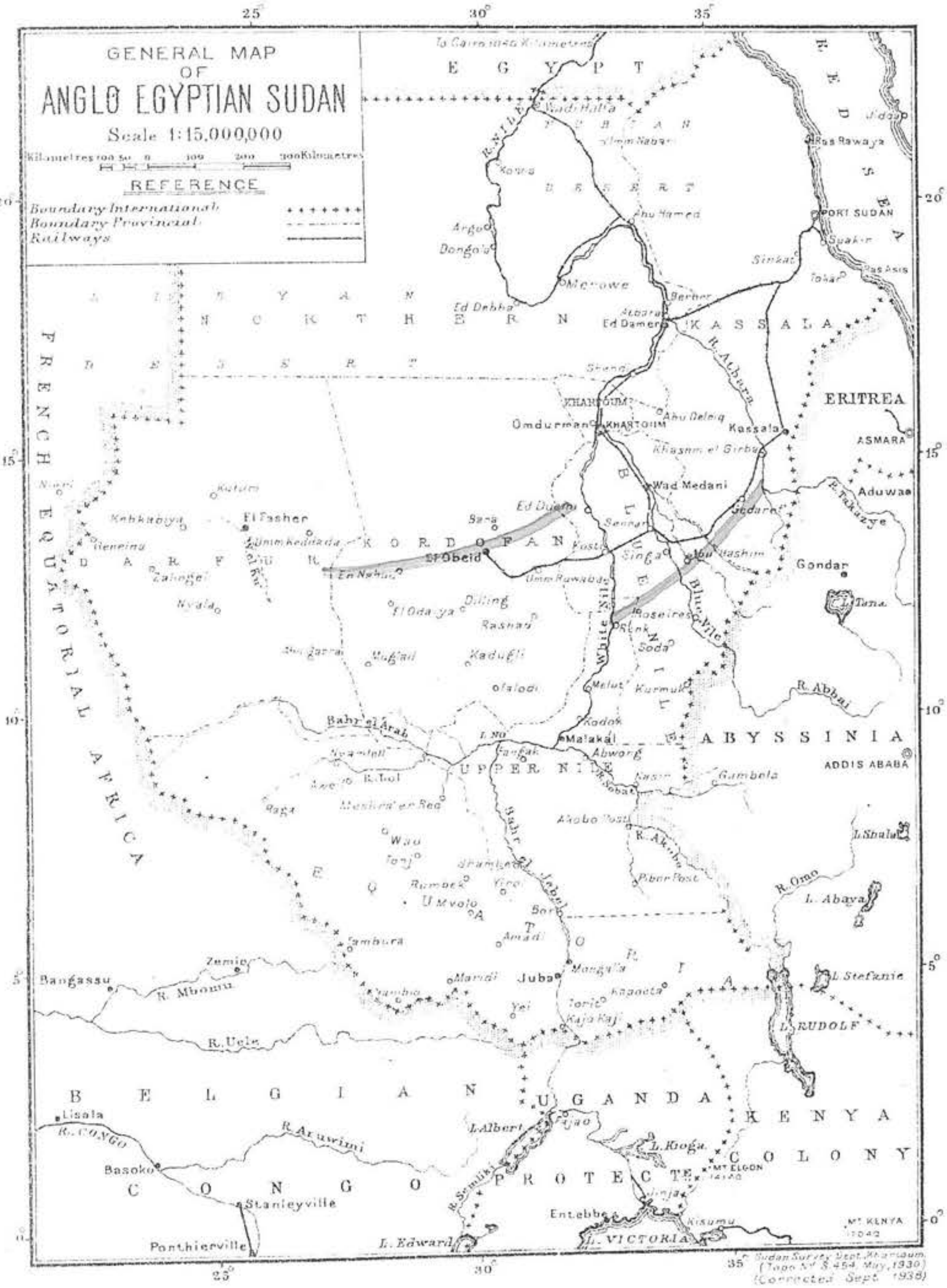
A. Lebecladoides

A. stenocarpa

Line of the Transect through Acacia spp. belts on Datum soils. See Part II Chap II A.(i)

Line of the Transect through species belts of the Mixed Deciduous Forest. See Part II Chap II A(ii)

PLATE IX



The two Belt axes of Acacia senegal

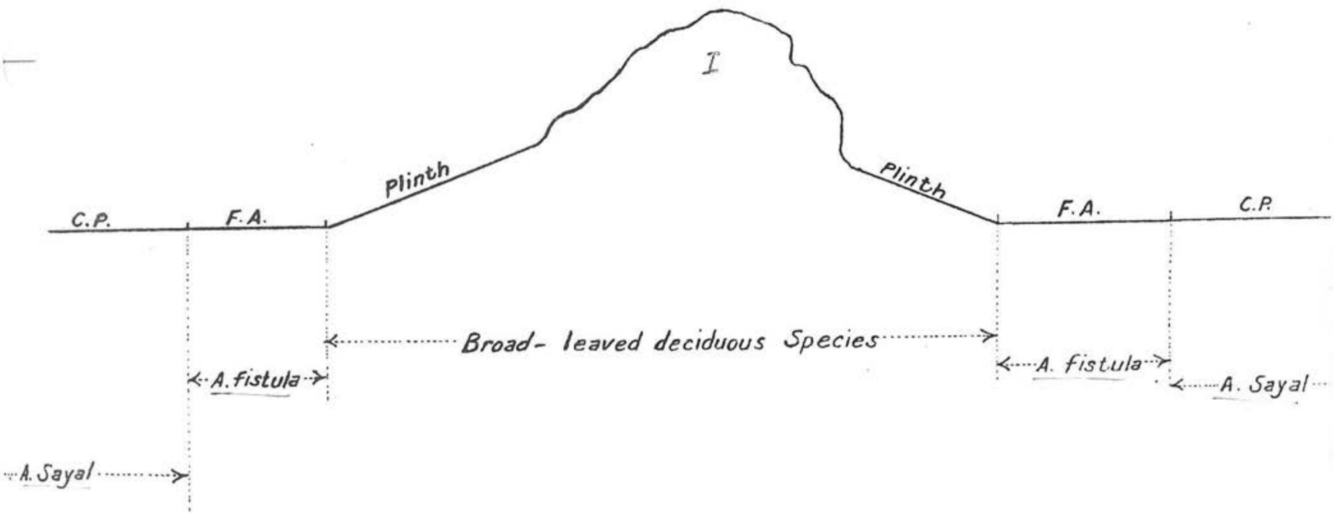
Western axis on sands in 400 mm of Rain

Eastern axis on clays in 600 mm of Rain

PLATE X

DIAGRAM OF AN INSELBERG IN A COTTON SOIL PLAIN.

Plate X

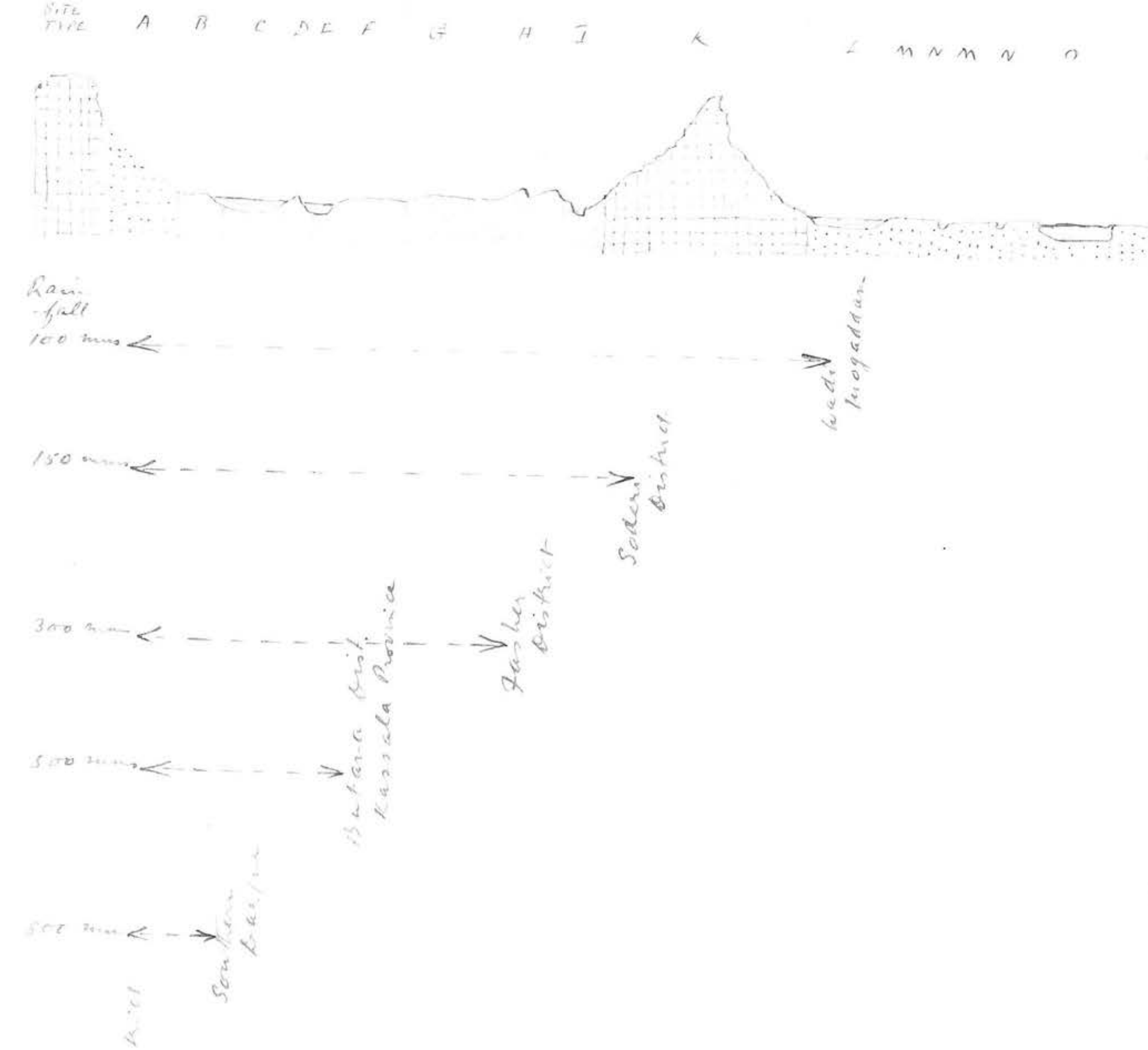


I. = Inselberg, or isolated hill in a flat plain.
Plinth = Halo of detritus surrounding the base of an inselberg like a collar.
F.A. = Flooded area of "cotton" soil plain; flooded seasonally by run-off from the plinth.
C.P. = Clay plain typical of the surrounding country for miles.

Plate XII

The Rainfall Transect for a single species
(See Part II Chapter III (iii))

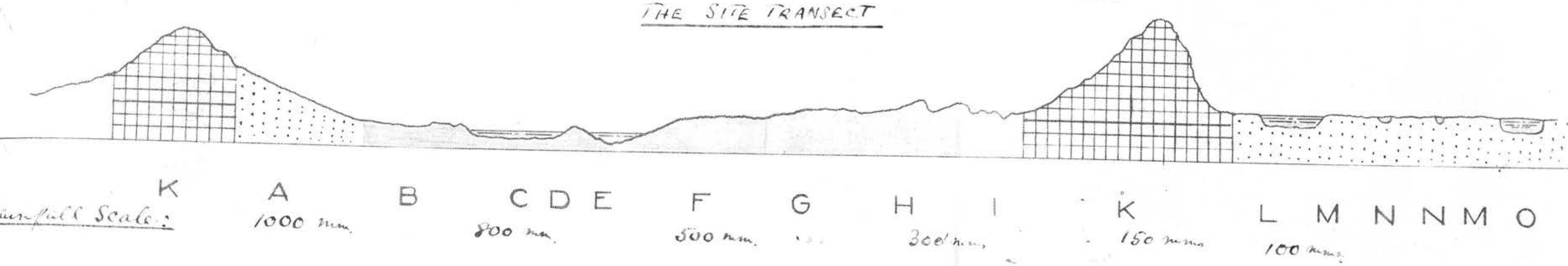
Species: Acacia mellifera.



The above diagram shows the changes in the type of site occupied by Acacia mellifera with changes in rainfall across a span of 1000 miles.
The Site types A – O have been described on Plate XI

PLATE XIII

THE SITE TRANSECT



The site Transect

See Part I Chap. II (iv) p. 35.

All species progress through their rainfall span [illegible] the same series of site types and in the same order of site types.
This diagram shows the series, the order, and the rainfall span within which these sites can be [illegible] as evidenced by the [illegible] on [illegible].
Not all the site types of this series are always represented in a single contour transect.
Comparison of site type above with the rainfall shown below it gives a measure of the [illegible] values in terms of [illegible], of the [illegible] site types.
The site types are described on Plate XI and at pp. 37–[illegible]

Plate XV

This diagram shows, for four of the commonest Acacia spp. separately, occurring on datum sites, the type species which occupy adjoining non-datum sites in the same rainfall, and their relative positions on the scale of moisture requirement. For description of the sites see Plate XI

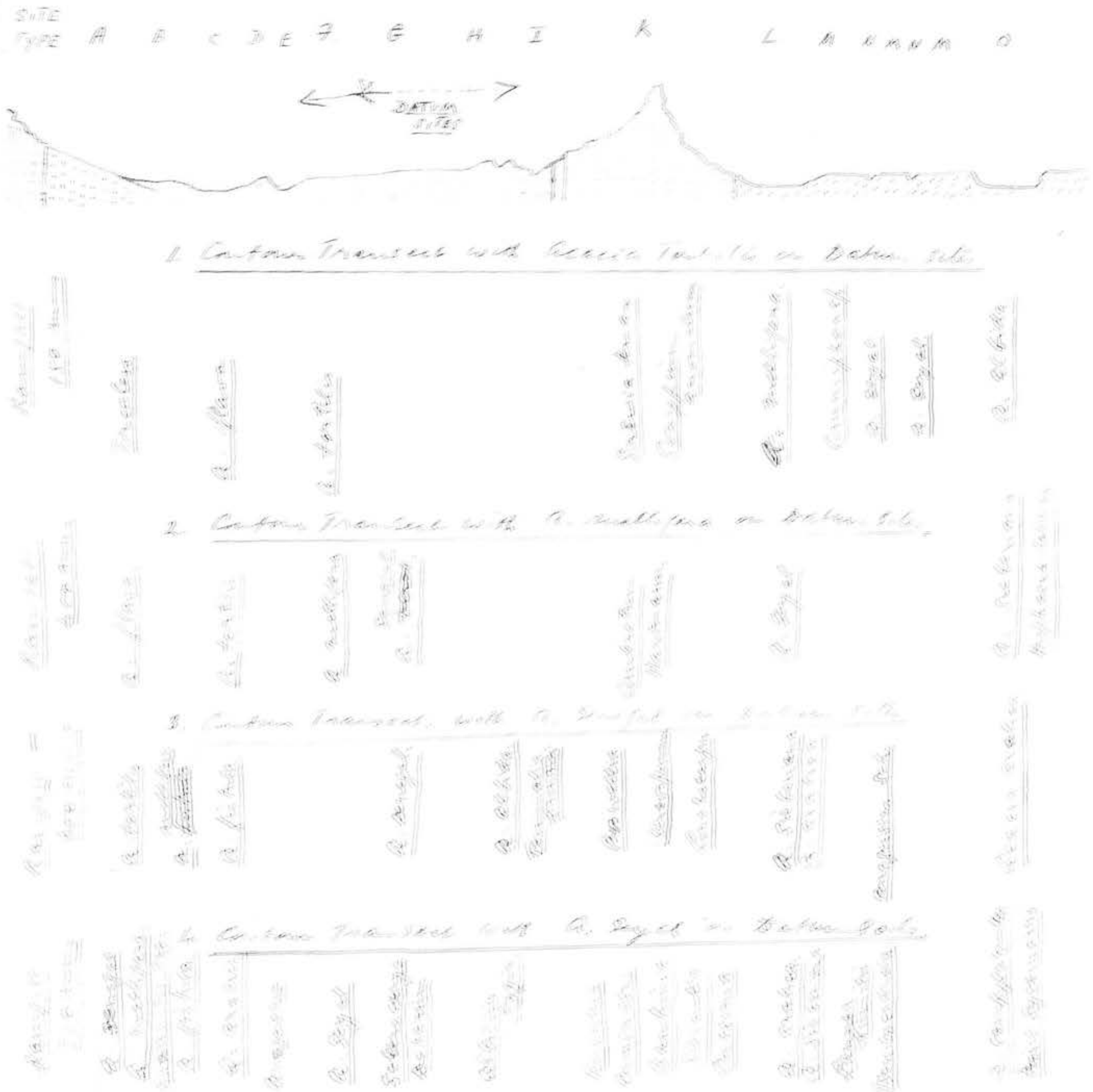
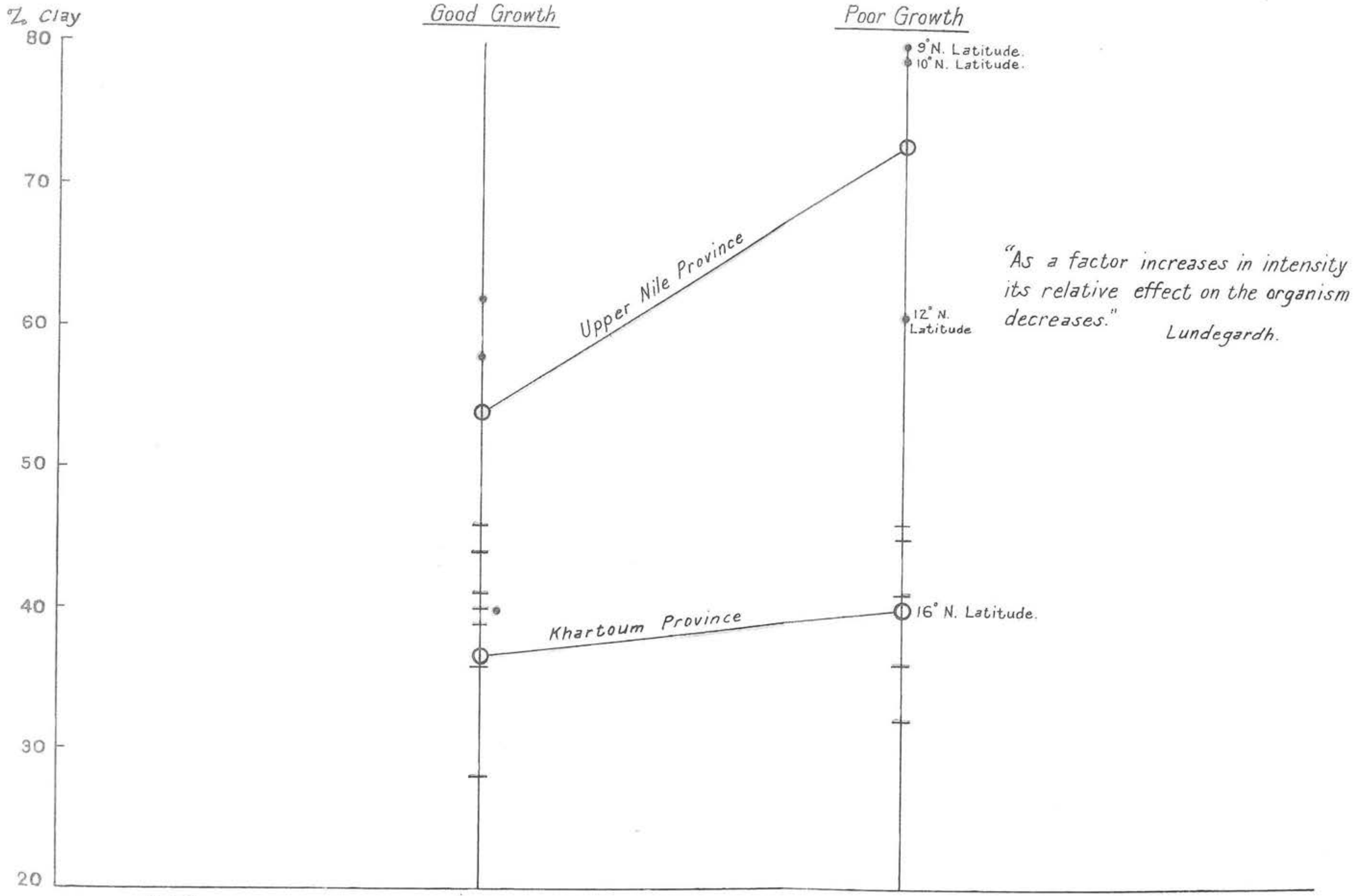


PLATE XVIII

Plate XVIII

DIAGRAM TO ILLUSTRATE VERSATILITY OF ACACIA ARABICA (WILLD)

in terms of clay content only, water supply not determinable owing to dual conditions of rainfall and inundation. See p. 43



NOTE.

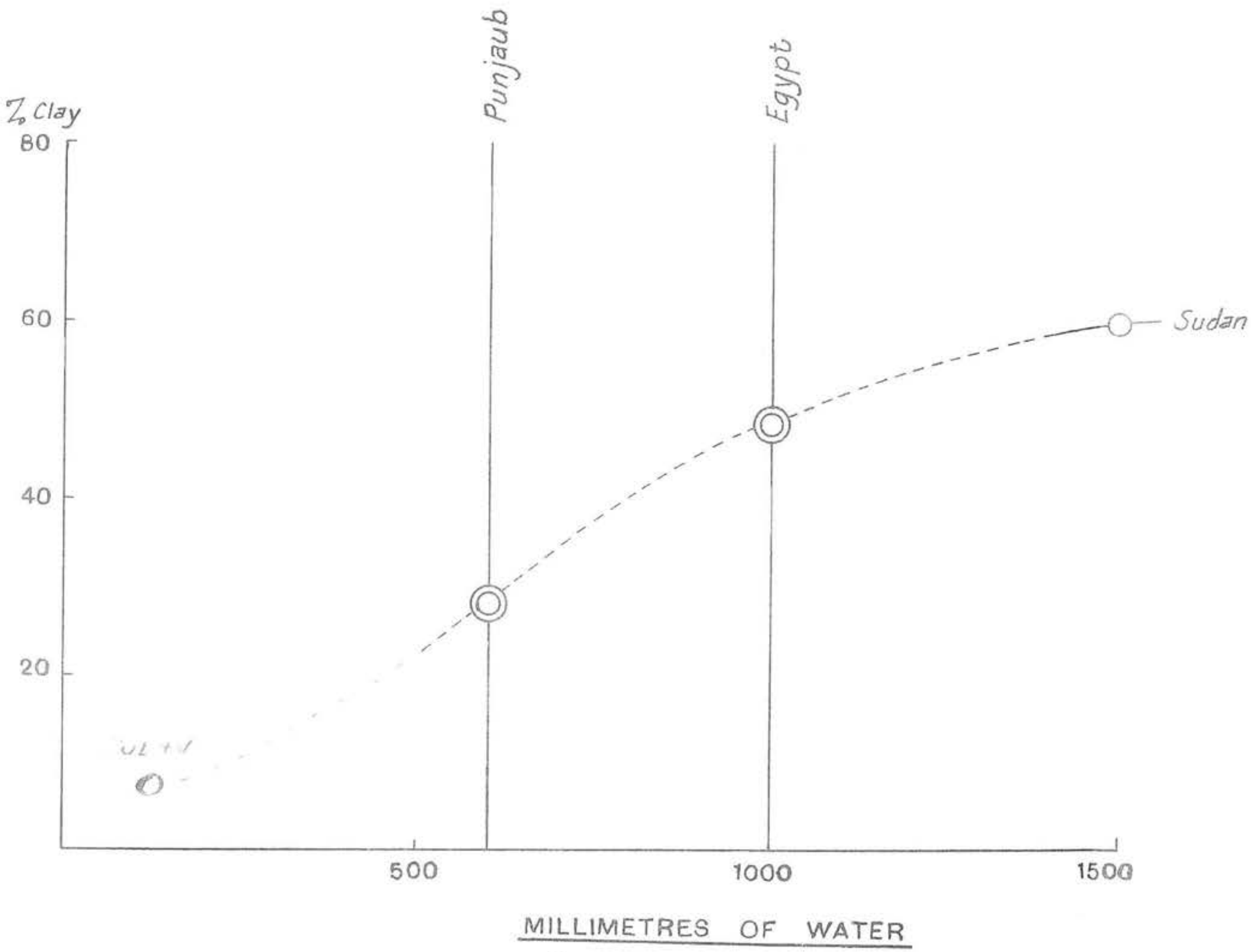
Sites within Natural Range in Blue.

Sites of artificial establishment outwith Natural Range in Red.

Averages of Natural & Artificial Sites good growth & poor growth joined by coloured lines.

Survey Dept, Khtm., Mar. 38 (Maps 199)

Plate XIX



See pp 41 and 47

Diagram showing the known clay water relation for Sakel Cotton in the Sudan Gezira and the known water requirement of cotton in Egypt (Dudgeon, Molesworth and Yenidunia) and in the Punjaub (Wilsdon) from Greene.

Point O is known. Points ◎ are intersections suggested as probable clay contents of the Punjaub & Egyptian Soils which have water requirements of 600 m/m. and 1000 m/m. respectively.

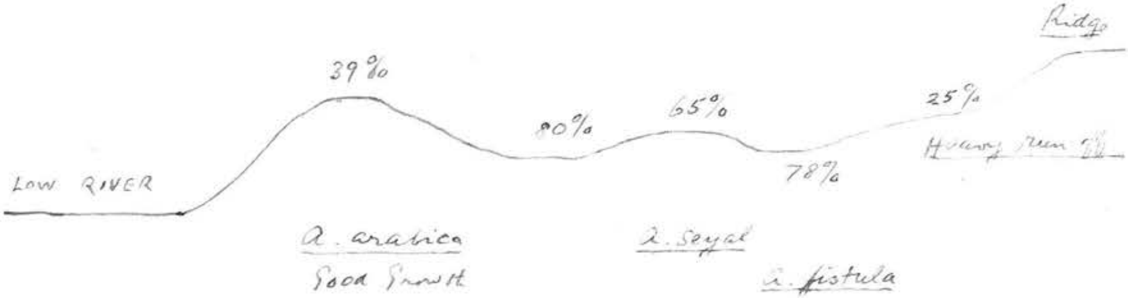
Point O represents the rainfall - soil-texture [illegible] existing at the [illegible] experiment with [illegible] Cotton on a Sand dune, described at p. 41

Survey Dept., Khartoum, March 1938. (Maps No 1399).

PLATE XX

VARIATION OF CLAY CONTENT WITH CONTOUR

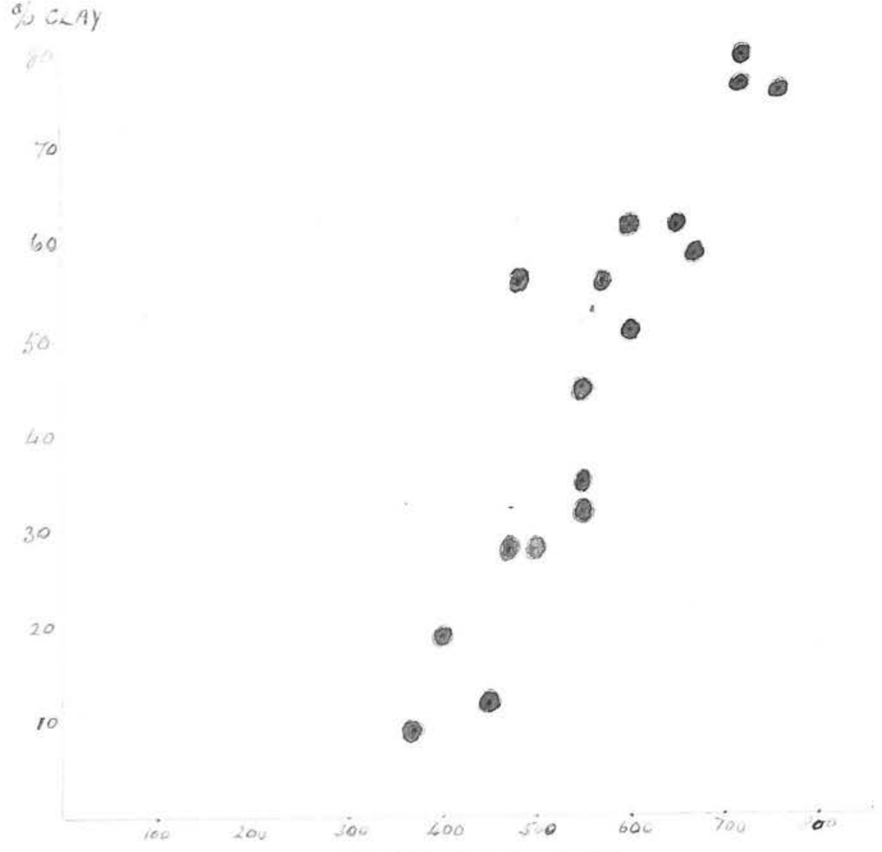
TEWFIKIA FOREST RESERVE.



See page 54 Part III Chap I B (iii)

PLATE XXII

The Clay-water line, or Rainfall-Soil Texture line, to give direction, for *Acacia Seyal* on natural sites.

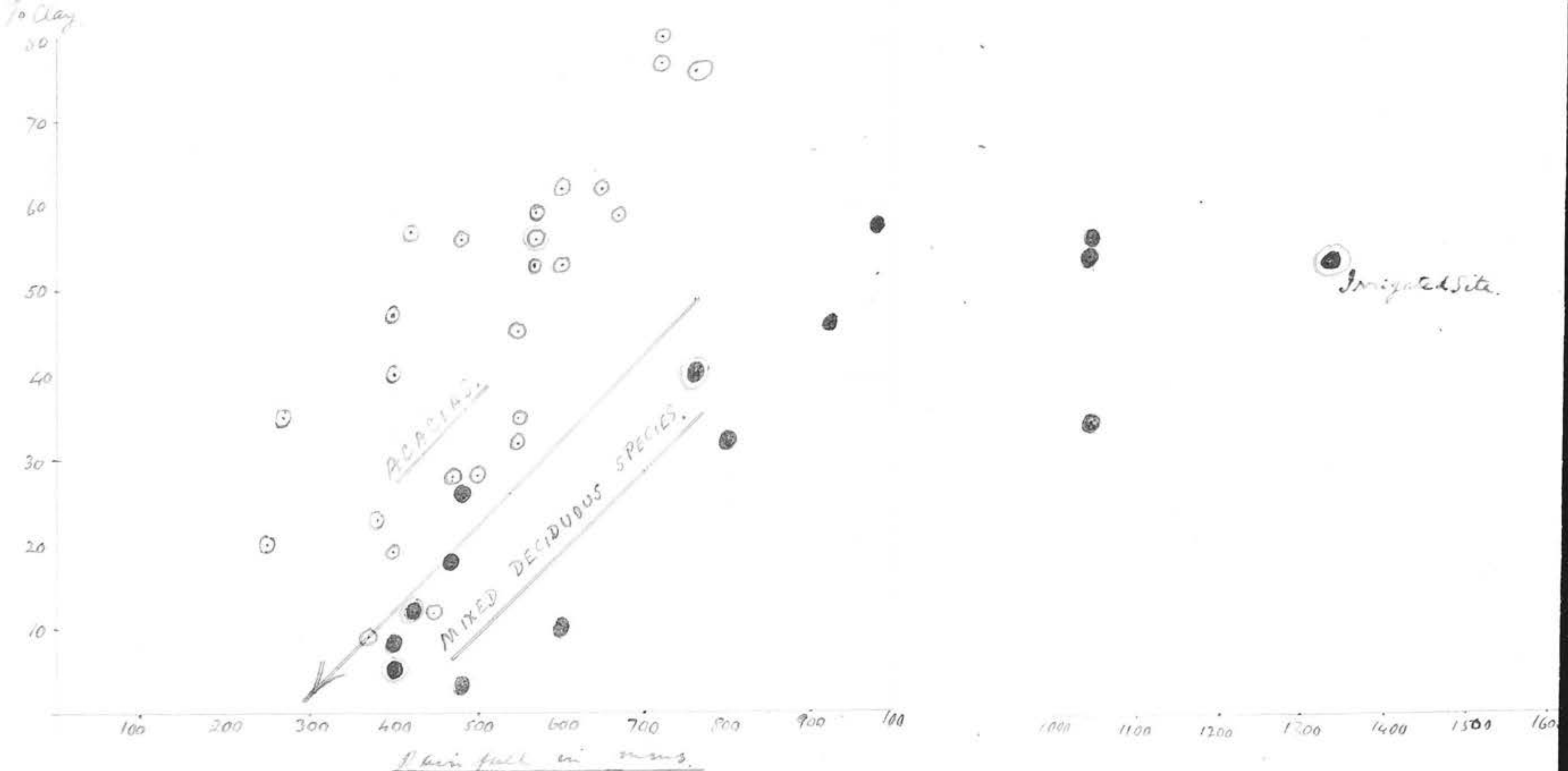


SITES:

Eridan Road	56%	480 mm	Gedid Ras el Fil	45%	550 mm
Gozair	56%	575 mm	E. of Buram	32%	550 mm
Kaka	62%	650 mm	Kobbi-Nyala	35%	550 mm
Um Berbeit	51%	600 mm	Kiringir-Sunni	53%	500 mm
Araderba	59%	670 mm	Kergulla	28%	500 mm
Zerzur	77%	720 mm	Garsilla	19%	400 mm
Um Berbeit	62%	600 mm	Geneina Road	9%	370 mm
Tewfikia	78%	760 mm	W. of Kalokitting	12%	450 mm
Zarzour	80%	720 mm	Ditto.	25%	450 mm

PLATE XXIII

Diagram to show the clay-water or rainfall-soil texture relationship between the two principal species of the Acacia belt namely A. mellifera ⊙ and A. seyal ⊙ and the mixed Deciduous species ● represented here by Khaya senegalensis ●, Prosopis oblonga and Combretum Hartmannianum.



The line is shown which divides the rainfall-soil texture conditions of natural clay soils in the Acacia belt from those of the mixed Deciduous forest

APPENDIX I

INDEX OF SPECIES IN ALPHABETICAL ORDER.

Abrus precatorius Linn.

Acacia abyssinica Hochst.
Acacia albida Del.
Acacia arabica Willd.
Acacia campylacantha Hochst. ex A.Rich.
Acacia drepanolobium Harms.
Acacia fistula Schwfth.
Acacia flava (Forsk.) Schwfth.
Acacia hebecladoides Harms.
Acacia laeta R.Br.
Acacia mellifera Benth.
Acacia mollissima (introduced).
Acacia orfota (Forsk.) Schwfth.
Acacia raddiana Savi. Arabic 'sayal'.

Acacia senegal Willd.
Acacia Seyal Del.
Acacia Sieberiana D.C.
Acacia stenocarpa Del. var multijuga Schwfth.
Acacia tortilis(Forsk) Christensen.

Adansonia digitata Linn.
Adenium Hongkel A.DC.
Afzelia africana Smith.
Albizzia anthelmintica A.Brogn.
Albizzia Aylmeri Hutch.
Albizzia sericocephala Benth. Syn. A. amara.
Albizzia maranguensis Taub.forma.
Albizzia zygia C.J.F.Macbr.

Alstonia congensis Engl.
Amblygonocarpus obtusangulus (Welw.ex Oliv.)Harms.
Annona chrysophylla Boj.
Arundinaria alpina K.Schum.
Anogeissus schimperi Hochst.
Antiaris toxicaria (Rumph.ex Pers)Leseh.
Avicennia marina Stapf.

Bauhinia reticulata DC.
Borassus aethiopium Mart.
Boscia senegalensis (pers.)Lam.ex Poir.
Boswellia papyrifera A.Rich.
Bridelia micrantha Baill.
Burkea africana Hook.
Butyrospermum niloticum Kotschy.

Capparis decidua Pax.
Cadaba rotundifolia Forsk.
Calotropis procera Ait.

Calotropis procera Ait.
Canarium Schweinfurthii Engl.
Capparis decidua Pax.
Carissa edulis Vahl.
Ceiba pentandra Gaertn.
Celtis integrifolia Lam.
Chlorophora excelsa Benth.& Hook.
Chrysophyllum albidum G.Don.
Cola cordifolia R.Br.
Combretum aculeatum Vent.
Combretum Hartmannianum Hochst.
Combretum ghasalense Engl.& Diels.
Cordia gharaf Ehrenb. ex Aechers.
Cordyla africana Lour.
Crossopteryx febrifuga Afz. ex G.Don.
Cussonia arborea Hochst. ex A.Rich.

Dalbergia melanoxylon Guill.& Perr.
Daniellia oliveri (Rolfe) Hutch.& Dalz.
Detarium senegalensis Gmelin.
Dichrostachys glomerata Hutch.& J.M.Dalz.
Diospyros mespiliformis Hochst.
Dombeya mucale Sprague.

Ekebergia senegalensis A.Juss.
Entanrophragma sp.
Erythrophlaeum guineense Don.
Entada sudanica SCHwfth.
Erythrina abyssinica Lam.

Fagara angolensis Engl.
Faurea speciosa Welw.
Funtumia elastica (Preuss.) Stapf.
Gardenia lutea Fresen.

Gardenia lutea Fresen.
Grewia tenax (Forsk.) Fiori.
Grewia mollis Juss.
Gossypium anomalum
Gossypium somalense
Gymnosporia senegalensis Lam.

Hagenia anthelmintica J.F.Gmel.
Herminiera elaphroxylon Guill. & Perr.
Hymenocardia acida Tul.
Hyphaene thebaica Mart.
Juniperus procera Hochst. ex A.Rich.
Irvingia Smithii Hook.f.
Imperata cylindrica Beauv. var Koenigii.
Isoberlinia angolensis Welw.
Isoberlinia Craib and Stapf. forma.
Isoberlinia doka Craib and Stapf.

dalzielii

Khaya grandifoliola C.DC.
Khaya senegalensis (Des V.) Juss.
Kigelia aethiopica Decne.

Landolhhia florida Benth.
Lannea fruticosa Hochst.
Lannea humilis Oliv.
Lannea velutina A.Rich.
Leptadenia Spartium Wight.
Lonchocarpus laxiflorus Guill.& Perr.
Lophira alata Banks ex Gaertn.

Maba abyssinica Hiern.
Maerua angolensis DC.
Maerua crassifolia Forsk.
Maesopsis eminii.
Mildbraedicdendron excelsum Harms.
Mimusops Kummel Hochst. ex A.DC.
Mitragyne inermis (Willd.) O.Kuntze.
Mitragyne stipulosa O.Kuntze
Monotes Kerstingii Gilg.
Oxytenanthera abyssinica (A.Rich.) Munro.
Olea Hochstetteri Baker.
Olea welwitschii (Knobl.) Gilg.& Schellenb.
Parinari curatellifolia Planch.ex Benth.
Parkia filicoidea Welw. ex Oliv.
Parkia oliveri Macbr.
Podocarpus gracilior Pilger.
Podocarpus milanjianus Rendle.
Panicum repens Linn.
Panicum turgidum Forsk.
Paspalidium geminatum Forsk.
Phragmites mauritianus Kunth.
Polyscias ferruginea (Hiern) Harms.
Prosopis africana(G.& P) Taub.
Prosopis juliflora.(introduced).
Protea abyssinica Willd.
Protea madiensis Oliv.
Pseudocedrela Kotschyii Harms.
Pterocarpus lucens Guill. & Perr. X
Pygeum africanum Hook.f.

Rhizophora sp.
Rubus sp.
Saccharum biflorum.
Salvadora persica Linn.
Sarcocephalus esculentus Afzel.
Schrebra macrantha Gilg. & Schellenb.
Sclerocarya Birrea Hochst.
Steganotaenia aralacea Hochst.
Sterculia setigera Del.
Stereospermum kunthianum Cham.
Strychnos spinosa Lam.
Suaeda monoica Forsk.

Tamarindus indica Linn.
Terminalia Brownei Fresen.
Tetrapleura tetraptera Taub.

Uapaca sansibarica Pax.
Vitex cuneata Schum. & Thon. syn. V. cienkowskii, Kotschy & Peyr.
Zizyphus Spina-Christi Lam.

Note: Three grasses are named in the text by their Arab names.
The genera probably are:

Andar	_Sorghum sp._
Annis	_Sorghum sp._
Anzora	_Hyparrhenia sp._

No conclusive determination has yet been reached for these.

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Note:-

The following works have not been available, so far, to the writer, but are recorded here as they appear to touch closely on parts of the subject matter of this paper :-

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